Why are Federal Funds Rates so Smooth?*

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Abstract

US monetary policy is characterized by a substantial degree of inertia. While in principle this may well be the outcome of an optimizing central bank behaviour, 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 use a novel *thick modeling* approach to incorporate model uncertainty into the identification of central bank's preferences. The robust *thick* policy rule shows the kind of smoothness observed in the data without resorting to implausible values for the preference parameters.

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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 on 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 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 interest rate changes in the policy makers' loss function can be justified on several grounds (see Woodford, 2002, Ch. 7; Goodfriend, 1991 and Lowe and Ellis, 1997). The empirical model proposed by Rudebusch and Svensson (1999), 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; Rudebusch, 2001 and Favero and Milani, 2001). For example, Rudebusch (2001) 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 rule to match the data badly relies on so large weights for the policy makers' aversion to interest rate changes as the theory cannot easily motivate. This suggests the potential for a strictly related issue, namely the identification of the Fed policy preferences. Indeed, 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, 2002; 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, if any, for an interest rate smoothing goal.

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, the observation of smooth policy rates can simply reflect the choice of a policy rule that would perform reasonably well over various alternative policy scenarios.

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 relevant 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 and Jeon (2001) to pool into a single policy rule a large number of specifications in a given class of nested models. In particular, we first let policy makers implement, at each point in time, some 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 US monetary policy in the last decade. First, potential misspecifications of the macroeconomic dynamics 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 did neglect model uncertainty would 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 studies. The *thick* modeling approach to 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, 1998, and Bernanke and Mihov, 1998). Furthermore, if the central bank faces an intertemporal optimization problem, then forecasting the behavior of the state variables 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 may be a suitable characterization of the macroeconomic dynamics (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 $y_t = 100 * \left(\log\left(Q_t\right) - \log\left(Q_t^*\right)\right)$ 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).

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 a structural relation 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 behavioral parameters of the economy, which is an important condition for drawing inference. For instance, Muscatelli and Trecroci (2001) show evidence that while the response of output to interest rate shocks has not significantly changed, the short-run correlation between output and inflation has shifted during the last two decades. To the extent that this can be ascribed to the productivity growth that has characterized the US economy since the late 80s, focusing on the sample 1987:3 - 2001:1, which corresponds to the tenure of Alan Greenspan as Fed chairman, it turns out to be beneficial to limit parameter variation. Indeed, one may argue that this period has been marked not only by an increasing macroeconomic stability and a lower inflation but also by the expectations of some form of inflation targeting (see Bernanke and Mihov, 1998), thereby reducing the significance of the Lucas critique.

We estimate individually 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 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.[1] 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 Muscatelli and Trecroci, 2001, and 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 (1999). This corresponds to set the instrument rate so as to bring at each point in time the target variables in line with the targets by penalizing any future deviation of the former from the latter. Following Rudebusch and Svensson (1999), 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 potentially 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.[2] 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

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[1] Moreover, the cross-correlation of the errors is 0.137, implying that the parameter estimates are not affected by the estimation method. Lastly, the Andrews' test (1993) cannot reject the null of stability for both equations.

[2] As argued in Dennis (2000), demeaning all variables does not affect the derivation of policy makers' preferences. Furthermore, our analysis is meant to identify the central bank parameters 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).

respectively and unlike in Rudebusch and Svensson (1999), 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*.

On the positive side, 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 inertia observed in the data. On the negative side, the desire for smoothing policy rates has little theoretical justification beyond the optimal delegation argument according to which the appointment of a central banker who pursues an alternative objective relative to the true social one may be welfare improving (see Woodford, 2002, Ch. 7).[3] However, it can be argued that high variability and frequent reversals in interest rate movements may lead to financial instability (see Goodfriend, 1991) as well as they may be interpreted by the private sector as an admission of earlier policy mistakes (see Lowe and Ellis, 1997), thereby being undesirable.

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[4]:

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

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).

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[3] Alternatively, monetary authority may wish to stabilize the level, rather than the change, of policy rates. Then, the presence of transaction frictions and/or a zero nominal interest-rate lower bound result in an utility-based loss function with an interest rate term which enhances social welfare (see Woodford, 2002, Ch. 6)

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

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:

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

with an Adjusted R^2 of 0.96.[5] The significant parameters show that the monetary authorities operate in a gradual manner by changing the funds rates in response to both inflation and output gaps. In particular, the first lag of the policy 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 (see Rudebusch, 1995, and Goodhart, 1997). Finally, the coefficients on the interest 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 with no model uncertainty

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 potentially interest rate volatility. Then, a simple way to recover these preferences is to assume that policy makers are acting optimally and, as a kind of revelation principle, to extract the relevant information from the observed policy decisions. The control problem described above shows that the reaction function estimates can be interpreted as convolutions of the behavioral parameters of the economy and those describing the central bank's preferences and therefore they are natural candidates for the purpose at hand.[6] 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),

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[5] McCallum and Nelson (1999) argue that in operational policy making the central bank does not observe (and respond to) the current state of the economy. Using four lags of funds rate, GDP inflation and CBO output gap as instruments does not change significantly neither the point estimates nor the standard errors of the feedback coefficients.

[6] Moreover, our optimal control problem satisfies the three necessary and sufficient conditions derived in Dennis (2000) to identify central bank policy preferences .

where the distance is measured by the sum of squared deviations over time.[7] 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 can be highly misleading in that they miss an important feature of actual monetary policy making.

At this point, it is useful to relate our results to several recent studies since there exists interesting differences and similarities. Favero and Rovelli (2002) 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 (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 frontier 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 by Cecchetti and Ehrmann (1999) are built upon a common empirical model of inflation and output, namely the one by Rudebusch and Svensson (1999), 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 (2002) do not distinguish between the Volcker's and the Greenspan's chairmanship.[8] In particular, Panel A shows the first two moments of the fitted policy rates whereas Panel B displays in columns the

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[7] 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.

[8] 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 (2002) 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.

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.

The first two lines of Panel B in Table 1 refer to the present work and the one by Dennis (2001).[9] On the one hand, 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 other hand, they rely upon extremely large parameters for interest rate smoothing which cannot be easily motivated within the optimal monetary policy literature.[10]

By contrast, the last two lines of Table 1, which refer to the works by Favero and Rovelli (2002) 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 rates.

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.

The structure of the economy proposed by Rudebusch and Svensson (1999), 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

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

[10] For instance, the utility based loss function in Woodford (2002, Ch. 6 and 7), albeit derived in a different class of models, implies a theoretical value of μ no greater than 0.28, which is based on stuctural estimates for the US economy.

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 (2001), Estrella and Mishkin (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 such an uncertainty. By contrast, Sack (2000), Salmon and Martin (1999) and Söderström (1999) show using unrestricted VARs and unrestricted policy rules that the response of monetary authorities may result quantitatively more moderate, although they conclude that multiplicative parameter uncertainty alone is not enough to replicate the kind of smoothness observed in the data.

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 (2001) shows that the slope coefficients on inflation and 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 reported above may be 'misleading' as no identification method takes such an uncertainty into account and only the point estimates of the model parameters enter the analyses. By 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.

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 to be 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 (2001), 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 Granger and Jeon (2001) and we label this approach to model uncertainty *thick modeling.* We keep all close specifications according to some statistical criterion, find their outputs that relate to the design of optimal monetary policy and pool these values. 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 also Goodfriend, 1991 and Woodford, 2002, Ch. 7).

An alternative approach to solve for model uncertainty is provided by the techniques of robust control (see Hansen and Sargent, 2001, chapters 6 and 8). This method specifies a risk function 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, 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'

The standard practice of econometric modelling is to choose among a set of relevant specifications the best according to some model selection criterion like *adjusted* R^2, *Akaike* or *Schwarz*, discarding any information in the alternative specifications. In practical policy making, however, it is not clear that this may be a good strategy and policy makers, who are uncertain about the future state of the economy, may find retaining and combining all information in a number of close specifications a superior strategy. The reason for that mirrors the results in the literature of optimal forecasting (and portfolio allocation) which demonstrate that the combination of forecasts (assets) is often a better procedure than using the best single forecast (asset). Then, *mutatis mutandis*, the monetary authority may prefer to consider the range of a wide number of optimal monetary policies, each one corresponding to the solution of the control problem associated to a different structure of the economy, rather than to come up with a single policy rule which is optimal only within the model specification in which it has been derived. In so doing, they may end up with as many policy prescritions as the number of relevant macroeconomic scenarios. To the extent that the latter differ in the lag specification of the monetary transmission mechanism and that policy makers have no strong *a priori* on the future state of the economy, the *thick* modelling of combining those prescriptions comes as a simple strategy for the design of a global optimal policy without requiring any restrictive decision about what model will provide the best description of the economy.

In practice, we specify a class of nested models for the structure of the economy and propose some *a priori* criterion to pool into a single robust *thick* 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 those models displaying 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 average of the optimal rates associated to those specifications.

A number of alternative weighting schemes may be appropriated for computing the average optimal policy. Instead of using a simple statistical pooling, Granger and Jeon (2001) argues that a simple averaging may serve for the purpose at hand, corresponding to what in the literature is usually refered to as a non-informative prior with equal weights given to different monetary policies. An alternative somewhat in the spirit of Bayesian econometrics is to weight the OLS estimates across models by some statistical criterion corrected for the degrees of freedom. Doppelhofer, Miller and Sala-i-Martin (2000) propose a weighting criterion analogous to the Schwarz in the context of the so-called Bayesian averaging of classical estimates (BACE), which has the advantage over the Bayesian model averaging of not requiring any specification of prior distributions for the model parameters.

These alternative weighting schemes describe the robust policy rules that we use in the next section to evaluate the ability of model uncertainty to account for the observed interest rate smoothing. Our *thick* strategy is in the spirit of Favero and Milani (2001), although we take three 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. Lastly, we evaluate the robustness of our results to different weighting schemes for averaging the optimal policies obtained under the alternative policy scenarios.

5 The Fed policy preferences under model uncertainty

In this section, we use our identification method to recover the preference parameters for the Greenspan's tenure in the presence of model uncertainty. In order to gauge the merits of the robust *thick* policy rule we compare our results with those obtained under a multiplicative parameter uncertainty which a number of researchers have advocated as an important, although not exhaustive, source of policy attenuation (see Sack, 2000, Sack and Wieland, 2000, and Rudebusch, 2001 among others).

It is worthy to note that in contrast to the analysis in section 3, 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 some average of the optimal rules for each of the relevant 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 misspecification by assessing the ability of a *robust* rule to match the data without resorting to implausibly high values for the interest rate smoothing parameter.

5.1 The robust thick policy rule

The third row of table 2 reports some descriptive statistics of the optimal rule under model uncertainty as well as the corresponding calibrated policy parameters. The revealed preferences for the Greenspan's chairmanship write now $\lambda = 0.00$ and $\mu = 0.11$ while the first two moments of the associated optimal path are consistent with the historical policy (first row). Moreover, the average distance is still fairly low and the standard deviation of the interest rate changes, which actually defines interest rate smoothing, remains virtually identical moving from the historical rule to the robust *thick* rule. While the statistics and the following figures on model uncertainty refer to the simple average case, the picture does not change, both qualitatively and quantitatively, weighting each optimal policy with the relative *adjusted* R^2, *Akaike* and *Schwarz* criterion respectively. In the light of our trimming strategy, this result does not come as a surprise since the closer are the retained specifications the more the weighted average tends to the simple average, that is the grater is the likelihood that similar weights are attached to each specification.

Figure 2 compares the two optimal paths associated to the preferences $\lambda = 0.00$ and $\mu = 0.11$ in the absence and under model uncertainty respectively. 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. 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 cannot be sensibly interpreted.

The revealed policy preferences computed under model uncertainty show that the conduct of monetary policy in the US is successfully described by a *strict inflation targeting* as defined by Svensson (1999), and Rudebusch and Svensson (1999). According to it, the stabilization of output around potential has not been a final concern of the Federal Reserve (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 (2002) 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, or yet, that the marked productivity growth of the 90s has drastically reduced any concern towards output stabilization.

5.2 Model uncertainty vs. parameter uncertainty

The result that uncertainty makes smoother an otherwise volatile path of policy rates does not come as new in the literature and a number of empirical studies have recently shown that multiplicative parameter uncertainty limits the responsiveness of the interest rate (see Sack, 2000 and the references therein). A relevant question at this point is the extent to which parameter uncertainty would be capable alone to replicate the observed path or rather there exists room for other forms of uncertainty. To this end, we bring together in the last two rows of table 2 some descriptive statistics for the robust policy rules obtained under model and parameter uncertainty respectively. We take as given the revealed policy preferences $\lambda = 0.00$ and $\mu = 0.11$, which assigns a very limited role to an interest rate smoothing goal, so that the performance of the robust rules can be readily compared. The computational difference between the two robust rules stems from the distribution of the AS-AD coefficients which only under parameter uncertainty are centered around our estimates of the Rudebusch and Svensson (1999) model and shaped by the relative estimated standard errors. By contrast, the robust *thick* approach does not impose any mean value to the parameter distributions whose support reflects a model specification uncertainty rather than the classical estimation uncertainty due to sampling.

The last row of table 2 shows that multiplicative parameter uncertainty attenuates the policy response of monetary authorities such that the relative robust descriptive statistics come closer to the data than the single specification counterparts. Nevertheless, the robust optimal policy seems to reduce but not to close the gap with the observed monetary policy confirming the conclusions in Sack (2000) and Rudebusch (2001). In addition, taking model uncertainty into account makes the robust *thick* policy rule more successful at describing the policy rate dynamics than the parameter uncertainty robust rule. This can be seen not only from the first two moments and the average distances but also, more importantly, from the standard deviations of the interest rate changes. Consistent with these findings, Figure 3 shows that the behavior of policy rates is considerably smoother under model uncertainty than under parameter uncertainty as the robust *thick* policy rule shows more limited deviations from the historical rule.

We interpret these results as the evidence that model misspecification has been an important concern of the Fed such that its ability to limit the responsiveness of the fed funds rate goes beyond the ability of a multiplicative parameter uncertainty.[11]

6 Conclusions

Actual policy rates appear to be smoother than optimal monetary policies predict. An obvious way to reconcile the historical evidence with an optimizing central bank behavior is to model the aversion to interest rate fluctuations as an independent argument in the central bank's loss function. However, the relative parameter should be imposed at values so high as they cannot be easily motivated by the theory, thereby making this choice alone unsatisfactory.

This paper contributes to the literature of optimal monetary policy by presenting a novel method to solve for a relevant form of uncertainty in practical policy making, namely uncertainty about the structure of the economy. While there may well be also other rationales such as data uncertainty or a minor goal to avoid interest rate variability, it is shown that the concern for potential misspecifications of the macroeconomic dynamics creates incentives for monetary authorities to move policy rates in a gradual manner. Indeed, a thich approach to model uncertainty appears to solve most of the observed *interest rate smoothing puzzle* as the preference calibration based on a robust policy rule returns values which are more readily interpretable. 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 returned 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. By contrast, our revealed preferences move to sensible values when the calibration incorporates a wide number of possible specifications. This seems to suggest that most of the observed policy inertia can be better interpreted as a consequence of mone-

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[11] It should be noticed that we have modelled parameter uncertainty as the perturbation of the slope coefficient of inflation and the interest rate sensitivity on output only. While varying all parameters produces only limited changes, an alternative would be to consider a richer macroeconomics dynamics as the one in a VAR specification of the economy. However, Sack (2000) shows that even involving very persistent interest rate movements, the optimal policy derived within a VAR dynamics is still more aggressive than the observed policy.

tary policy making under uncertainty rather than as an objective in itself and that omitted model uncertainty may lead to the spurious finding of an independent goal for interest rate smoothing.

Furthermore, our robust *thick* modeling can be extended to alternative formulations of the inflation dynamics and the output gap dynamics in order to evaluate the empirical relevance of model uncertainty within a class of non-nested specifications. Lansing and Trehan (2001), for instance, show that by introducing some degree of forward-looking behavior in output, the responses to inflation and output gap recommended by an optimizing Taylor rule are less pronounced. In particular, they show that private sector expectations may be an important channel through which monetary policy can be effectively conducted by means of small interest rate changes (see also Levin, Wieland and Williams, 1999, Sack and Wieland, 2000, and Castelnuovo, 2003). However, Söderlind, Söderström and Vredin (2002), who calibrate the preferences of the Fed within a New-Keynesian model of output and inflation, still find a large value for the policy parameter on interest rate smoothing. This suggests that model uncertainty about the relevant macroeconomic dynamics may turn out to be an issue also in such a framework and therefore further work can be usefully done along these lines.

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:

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

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

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

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:

$$Y_t = \begin{bmatrix} \bar{\pi}_t \\ y_t \\ i_i - i_{t-1} \end{bmatrix}, \quad C = \begin{bmatrix} \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 \end{bmatrix}, \quad D = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \tag{19}$$

Accordingly, the loss function can be rewritten as:

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

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:

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

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:

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

This implies the following feedback rule for the policy instrument

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

where f is given by:

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

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

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

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*
0.000	1.7307

Panel B: Descriptive statistics, policy preferences and average distance of the optimal 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 (2002)**	$\lambda = 0.00125$ $\mu = 0.00850$	0.3564	16.9932	41.5373
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.

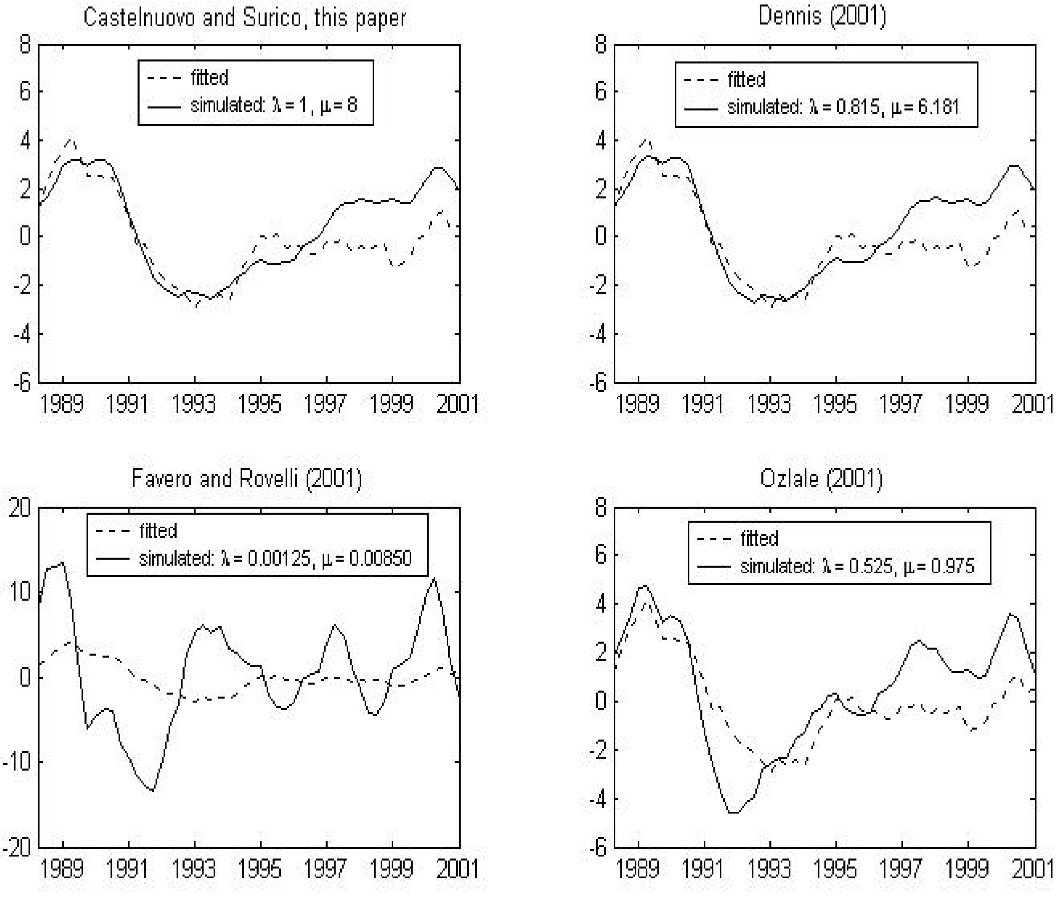
Note: the preference parameter on inflation stabilization is normalized to one. The parameter on output stabilization is denoted by λ while the one on interest rate smoothing is μ. The average distance is measured as the mean of the sum of the squared deviations between optimal and fitted policy rates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

Table 2 – Optimal monetary policy rules and uncertainty: descriptive statistics

Optimal Rules	*Estimates*	*Mean*	*Standard deviation of interest rate levels*	*Standard deviation of interest rate changes*	*Average distance*
Fitted policy rule	- -	0.000	1.7307	0.5207	-
Thin policy rule	$\lambda = 0.000$ $\mu = 0.111$	0.4635	4.2493	1.2980	11.4717
Thick model uncertainty robust policy rule	$\lambda = 0.000$ $\mu = 0.111$	0.0087	1.8024	0.5165	2.0385
Parameter uncertainty robust policy rule	$\lambda = 0.000$ $\mu = 0.111$	0.3051	2.9353	0.8439	3.5341

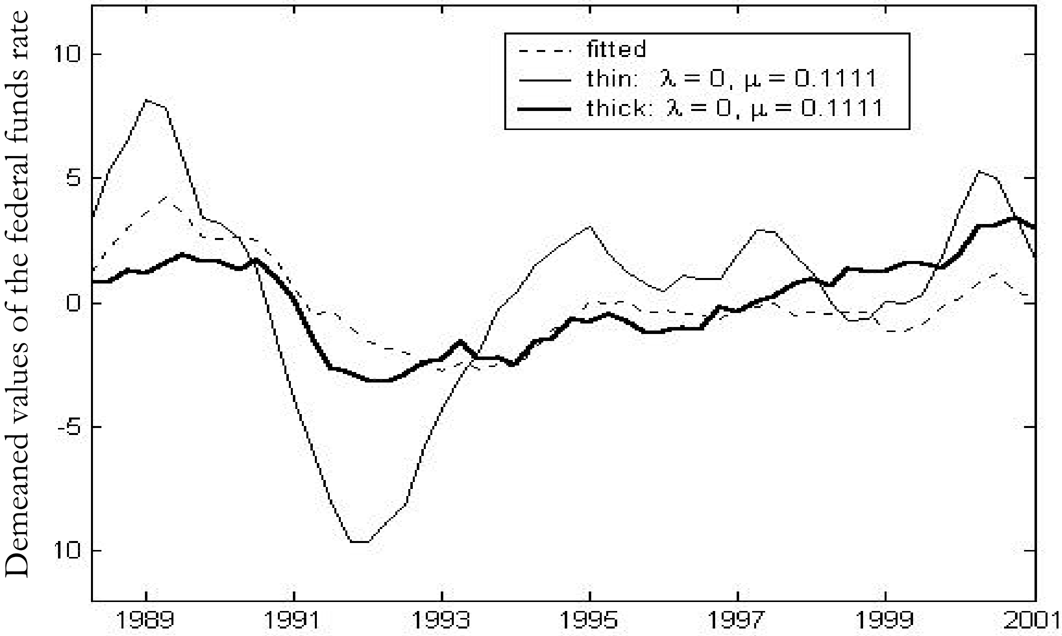
Note: the preference parameter on inflation stabilization is normalized to one. The parameter on output stabilization is denoted by λ while the one on interest rate smoothing is μ. The average distance is measured as the mean of sum of the squared deviations between optimal and fitted policy rates at 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. The parameter uncertainty robust policy rule is computed as multiplicative uncertainty on the key coefficients a_5 (slope of the Phillips curve, equation (1) in the main text) and b_3 (semi-elasticity of the output-gap with respect to the real interest rate, equation (2) in the main text). The uncertainty is determined upon the Variance-Covariance matrix of the OLS estimators.

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



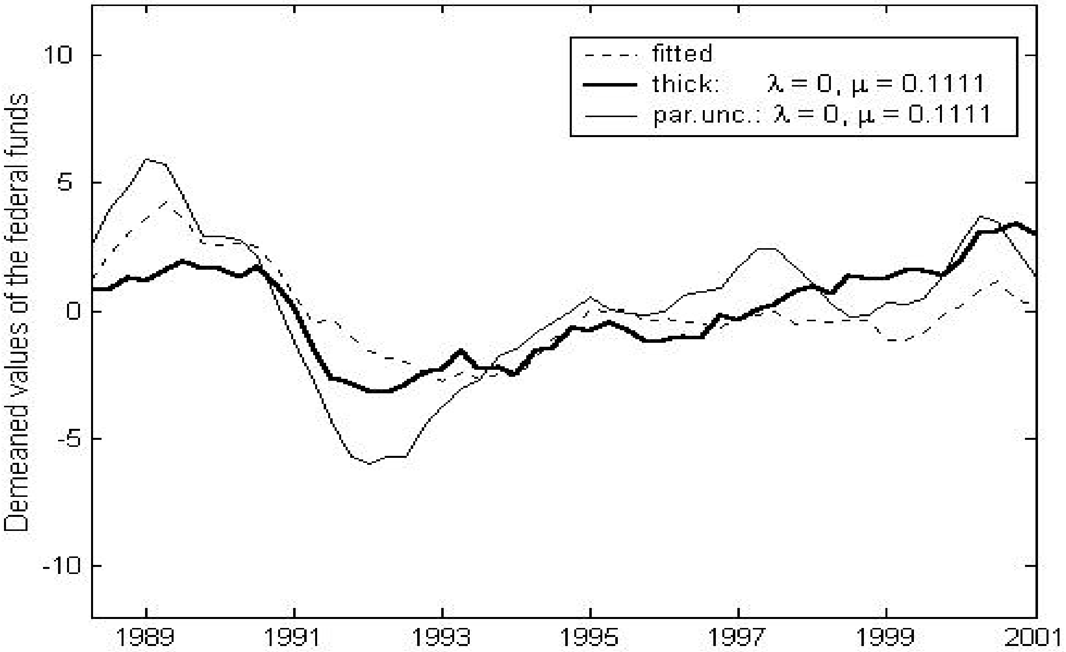
Note: the preference parameter on inflation stabilization is normalized to one. The parameter on output stabilization is denoted by λ while the one on interest rate smoothing is μ. Each optimal path shows the values that the funds rate would have taken if the Fed had historically implemented that optimal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

Figure 3 - Model vs. parameter uncertainty



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 model uncertainty 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. The parameter uncertainty robust policy rule is computed as multiplicative uncertainty on the key coefficients a_5 (slope of the Phillips curve, equation (1) in the main text) and b_3 (semi-elasticity of the output-gap with respect to the real interest rate, equation (2) in the main text). The uncertainty is determined upon the Variance-Covariance matrix of the OLS estimators.