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What does Monetary Policy Reveal about a Central Bank's Preferences?*

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The design of monetary policy depends on the targeting strategy adopted by the central bank. This strategy describes a set of policy preferences, which are actually the structural parameters to analyse monetary policy making. Accordingly, we develop a calibration method to estimate a central bank's preferences from the estimates of an optimal Taylor-type rule. The empirical analysis on US data shows that output stabilization has not been an independent argument in the Fed's objective function during the Greenspan's era. This suggests that the output gap has entered the policy rule only as leading indicator for future inflation, therefore being only instrumental (to stabilize inflation) rather than important per se.

(J.E.L.: C61, E52, E58).

1. Introduction

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

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[1] These include Bernanke and Mihov (1998) and Bagliano and Favero (1998) who specify the policy rule as a part of monetary policy vector autoregressions; Judd and Rudebusch (1998) and Clarida *et al.* (2000) who formulate a simple *ad hoc* reaction function; and Rudebusch (2001) and Muscatelli *et al.* (2002) who model an optimal state-contingent feedback rule, among many others.

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

In contrast, the preference parameters in the central bank's objective function capture those structural features, so rendering their estimation very informative for three main reasons; first, to improve our understanding of policy actions because any decision can be more easily interpreted once the scope is identified; second, to assess the performance of monetary policy by establishing if the policy outcome is the pursued result of targeted policies rather than the random pay-off of favourable macroeconomic conditions; and third, to carry out policy evaluations from the comparison between optimal and observed interest rates, since a sample-specific optimal rule can only be derived once the preference parameters are estimated over that sample.

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

Our work is closely related to some recent studies. Favero and Rovelli (2001) identify the Fed's preferences by estimating via GMM the Euler equations for the solution of alternative specifications of the optimization problem. Dennis (2001) uses FIML to jointly estimate the policy preferences in the Fed's objective function and the behavioural parameters in the constraints of the economy. Cecchetti and Ehrmann (2001) capture the dynamics of the economy in a VAR framework and then recover policy makers' preferences from the estimates of the output-inflation variability consistent with a simplified AD-AS model. While our purpose stands by those of previous studies, we take from them two important departures; first, we use a different sample, which is restricted to a single administration on the reasoning that policy preferences are Chairman-specific; and second, we employ a different estimation method (i.e. calibration) relative to earlier contributions.

The paper is organized as follows. Section 2 sets up the model and solves the optimization problem relevant to the central bank. Section 3 discusses in details the calibration method, which is applied in Section 4 to identify the Fed policy preferences during the Greenspan tenure. Section 5 concludes, while the Appendix provides a guideline to the numerical solution of the optimal control problem.

2. The Model

The central bank faces a dynamic optimal control problem whose solution describes its policy actions. These are the optimal response of monetary authorities to the evolution of the economy as captured by the relationships among the state variables. We describe such dynamics by means of a simple closed economy–two equation framework comprising an aggregate supply and an aggregate demand, these representing 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 (Christiano *et al.*, 1998; Bernanke and Mihov, 1998). Furthermore, if the central bank faces an intertemporal optimization problem, then forecasting the behaviour of the state variables (i.e. inflation and output gap) becomes crucial to set policy rates as the optimal response to the developments in the economy. In formalizing the economic structure, we focus on these AS–AD dynamic equations:

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

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

where π_t is the quarterly inflation in the GDP chain-weighted log-price index, p_t, calculated at annual rate, that is $400 * (p_t - p_{t-1})$, and $\bar{\pi}_t$ is four-quarter inflation constructed as $\frac{1}{4}\Sigma_{j=0}^{3}\pi_{t-j}$. The quarterly average federal funds rate, i_t, is expressed in per cent per year whereas the four-quarter average federal funds rate, $\bar{\imath}_t$, is computed as $\frac{1}{4}\Sigma_{j=0}^{3} i_{t-j}$. Supply and demand i.i.d. shocks are denoted by ϵ_t and u_t respectively. All variables but the funds rate are in logs and scaled up 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. All variables are demeaned; 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; 2002).

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 (Christiano, *et al.* 1996), 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). For the purpose of monetary policy making, which relies on forecasting method, a backward-looking model is likely to be preferred to a forward-looking one since the former overperforms the latter in fitting the data (Fuhrer, 1997). Notably, a backward-looking model does not show counterfactual dynamic responses to shocks hitting the economy, as those implied by the use of fully forward-looking models (Estrella and Fuhrer, 2002). 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 dynamics can be interpreted either as structural relations, or as a reduced-form restricted VAR with impulse responses.

2.2. The Loss Function and the Optimal Monetary Policy

We assume that monetary authorities operate by following a *targeting rule* as defined in Svensson (1999a), and Rudebusch and Svensson (1999).[2] Thus, they use all available information to bring at each point in time the target variables in line with their targets by penalizing any future deviation of the former from the latter. Following Rudebusch and Svensson (1999; 2002), we let the central bank pursue the stabilization of the four-quarter inflation

[2] Accordingly, we label 'target variables' the variables in the objective function (and not those in the reaction function). Our terminology lines up with the one in Walsh (1998, ch. 8), Clarida *et al.* (1999), Rudebusch and Svensson (1999) and Svensson (1999c).

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.[3] Then, policy rates are set to minimize the objective function

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

The quarterly average short-term interest rate, i_t, is regarded as the instrument under policy makers' control whereas Δi_t represents its first difference. The parameters λ_π and λ_y are the focus of our analysis and, unlike in Rudebusch and Svensson (2002), who set them exogenously, they are calibrated in our exercise. They represent the central bank's policy preferences towards inflation and output stabilization respectively. We constrain both parameters to be non-negative meaning that the central bank values any deviation of either inflation or output from the target as a *bad*. Finally, we normalize the weights in the objective function to sum up to one and, in accordance to Rudebusch and Svensson (1999, 2002), we assume $\lambda_{\Delta i} = 0.2$.

The optimal control problem described in (1)–(3) falls in the class of dynamic programming problems characterized by a quadratic objective function and a linear law of motion. This 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

$$X_t' = [\pi_t \quad \pi_{t-1} \quad \pi_{t-2} \quad \pi_{t-3} \quad y_t \quad y_{t-1} \quad i_{t-1} \quad i_{t-2} \quad i_{t-3}] \tag{4}$$

In particular, the central bank minimizes the loss (3) subject to the dynamic constraints (1) and (2). In so doing, it determines an optimal reaction function that can be expressed in the compact form:[4]

$$i_t = fX_t \tag{5}$$

The coefficients in the row vector f represent some convolution of the central bank's preferences, λs, and the behavioural parameters of the economy, αs and βs, such that, for any given distribution of weights in (3), there exists a different optimal f in (5).

2.3. *On Monetary Policy Gradualism*

The specification in (3) is empirically attractive since, unlike alternative monetary models as the FRB–US, it is able to predict an interest rate path

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

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

that exhibits the kind of smoothness observed in the data (Clarida *et al.*, 2000; Muscatelli *et al.*, 2002).[5] Indeed, a number of explanations have been recently advocated in the literature to regard interest rate smoothing as the outcome of an optimization process; in what follows, we attempt to give acknowledgement to the most popular examples.

Private Sector Expectations

In the absence of a commitment technology, the central bank cannot manipulate private sector's expectations through the promise of fighting inflation because such an optimal plan is not time-consistent in the sense of Kydland and Prescott (1977). As a consequence, Society is made worse off relative to the equilibrium associated to the commitment solution (Rogoff, 1985). A simple way to reduce the gap existing between discretion and commitment has been recently proposed by Woodford (1999). The idea is to endow the central bank with an interest rate smoothing goal, which is a goal to control the volatility of interest rate *changes*. In doing so, an optimally behaving central bank would implement an inertial interest rate close to the one that it would set under commitment. In other words, the expectations of monetary policy inertia, as induced by the private sector's understanding of an interest rate smoothing objective, can be thought as if the central bank committed to a future path of the interest rate.

Parameter Uncertainty

In the real world, monetary policy making is an exercise undertaken in an uncertain environment (Goodhart, 1999). Indeed, the central bank does face a lack of information concerning the monetary transmission mechanism. One of these uncertainties dates back to the seminal contribution of Brainard (1967) and regards the parameters attached to the model of the economy that the central bank is assumed to face. The monetary authorities, who are partially ignorant about the key parameters of the economy, may want to implement prudent monetary actions in response to shocks in an effort to reduce the 'uncertainty cost'. The latter is the possibility of inducing a large volatility in the economy due to a misrepresentation of the monetary transmission mechanism. Söderstrom (1999)

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

and Sack (2000) empirically demonstrate that, in an optimal control context with VAR representations of the economic dynamics, it is possible to replicate fairly well the federal funds rate path if taking into account parameter uncertainty.

Model Uncertainty

McCallum (1999) sustains that a good policy rule is the one that is capable to perform well across different models. In fact, a central bank is uncertain not only about the key parameters of the equations formalizing the economy, but also about the formalization of the whole economic framework. Empirical contributions by Favero and Milani (2001) and Castelnuovo and Surico (2003), conducted in a class of linear backward model, show that considering many diverse models may lead the central bank to implement a gradual, optimal monetary policy. Indeed, model uncertainty may be an important component in tracking the central bank's historical policy rate path.

Learning

Sack (1998) shows how a central bank that periodically refines his estimates of the key-parameters linking the variables of interest in a given framework may choose to act gradually. This result is due to the stochastic features of the economic dynamics, which render particularly informative the most recent observations. As a result, the Fed faces more uncertainty about the reaction of the economy the more it moves the funds rate away from its recent levels.

Data Uncertainty – Measurement Error

Orphanides (1998) offers an important contribution regarding the noise affecting the data. The argument runs as follows: the central bank should respond to shocks gradually, because it is difficult to understand if the one under consideration is a pure economic shock, or just a measurement error (or a mix between the two). Indeed, when simple rules *à la* Taylor (1993) are taken into account, the increase in volatility caused by measurement errors matters.

Financial Markets Reaction

A cautious monetary policy may also reflect the attention that the central bank poses to the reactions that financial markets exert after a monetary policy decision. Along this line, Goodfriend (1991) argues that the markets could over-react to a series of swings of the reference nominal rate such as to affect negatively the real side of the economy.

3. Calibrating Greenspan's Preferences

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

We estimate the reaction function in (5) and we solve numerically the stochastic optimal linear regulator problem for alternative targeting policies (i.e. for alternative distribution of weights λs in the loss function). Among those, we select the pair $[\lambda_\pi, \lambda_y]$ that makes the associated optimal interest rate path closest to the fitted path, which comes from the estimation of the optimal state-contingent rule derived in (5). In so doing, *de facto*, we are calibrating the central bank's preferences relevant for the period under analysis. Notice that, by defining our measure of distance on the *fitted* rather than the *actual* rate, we are restricting our attention to the systematic component of policy rate behaviour, that is, to the component that we can explain within an optimal control framework.

Our calibration strategy can be seized in five steps:

1 *Constraint estimates* We estimate the AD–AS system as specified in (1) and (2). The estimates roughly summarize the structure of the economy over a given sample and they will enter the recursive formulation of our simulated economy.

2 *Reaction function estimates* We estimate the reduced form reaction function derived in (5) and we call $\hat{i}_t = \hat{f} X_t$ the fitted value of policy rate at time t, where $\hat{f}$ is the vector of feedback coefficient estimates.

3 *Optimal control problem solution* Since a variation of the set of policy makers' preferences $[\lambda_\pi, \lambda_y]$ implies a modification of the feedback coefficients in the optimal rule, we solve the stochastic optimal linear regulator problem for many different targeting policies. In other words, we compute numerically as many vectors of optimal feedback coefficients f in (5) as the number of possible permutations of the λs over the range $[0, 1 - \lambda_{\Delta i}]$, where steps are one percentage point basis.

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

5 *Policy preference calibration* Finally, we select the set of policy preferences capable to deliver the minimum distance between fitted and optimal interest rate according to a canonical measure of the type proposed in Sack (2000) and Cecchetti *et al.* (2002).

$$\sum_t [i_t(\lambda_\pi, \lambda_y) - \hat{i}_t]^2 \tag{6}$$

3.1. Differences between our Econometric Strategy and Others Employed in the Literature

Interestingly, our estimation strategy differs from those employed by Dennis (2001) and Favero and Rovelli (2001). With respect to the former (i.e. FIML approach), our method is likely to be more robust to misspecifications in the error term since it does not depend on the distribution of the supply and demand disturbances. This does not come for free as our method does not produce standard deviations for the point-estimates. As the FIML strategy, our calibration is a full information strategy in that it jointly takes all into account the equations of our economic problem. The GMM methodology applied by Favero and Rovelli (2001) hinges as well on the estimation of a three-equation system comprising an aggregate supply curve, an aggregate demand and the monetary policy rule that solves the policy makers' optimization problem. Their results rely on the imposition of a finite policy horizon (of four quarters) to the central banker's problem, imposition that is not necessary in our study. Finally, our approach takes into account the representation of the economy when solving the optimal stochastic regulator problem. By contrast, Cecchetti and Ehrmann (2001) estimate a VAR for capturing the economic dynamics, but refer to a simpler model to estimate the structural preferences of the central banker.

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

4. The Conduct of Monetary Policy in the USA

In this section, we apply our calibration method to US data. Our goal is to identify the Federal Reserve policy preferences over a given period and to establish the sensitivity of these results to robustness and stability analyses. A natural time-break candidate for sample selection is the appointment of Paul Volcker in the October 1979 since it has represented the watershed for the US economy from an high to a low inflation era. However, with a backward-looking model, the selection of a long time-horizon may undermine the stability of the behavioural parameters, which is an important condition for drawing inference and surviving the Lucas critique (1976). It follows that the selection of an inappropriate sample may undermine the stability of the behavioural 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 1980s, 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 (Bernanke and Mihov, 1998), thereby reducing the significance of the Lucas critique.

4.1. A Small Empirical Model of the US Economy

We capture the dynamics of the US economy from 1987:3–2001:1 by applying OLS method to the AD-AS system described in (1) and (2). The potential output is obtained from the Congressional Budget Office whereas all other data are taken from the website 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.

The estimates are (with standard errors in parenthesis):

$$\pi_{t+1} = \underset{(0.133)}{0.282}\,\pi_t - \underset{(0.134)}{0.025}\,\pi_{t-1} + \underset{(0.134)}{0.292}\,\pi_{t-2} + \underset{(0.136)}{0.385}\,\pi_{t-3} + \underset{(0.054)}{0.141}\,y_t + \hat{\varepsilon}_{t+1} \tag{7}$$

$$y_{t+1} = \underset{(0.136)}{1.229}\,y_t - \underset{(0.149)}{0.244}\,y_{t-1} - \underset{(0.078)}{0.073}(\bar{i}_t - \bar{\pi}_t) + \hat{u}_{t+1} \tag{8}$$

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.[6] 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 USA over recent samples; see, for instance, Dennis (2001). Finally, although these estimates suggest a minor

[6] The cross-correlation of the errors is 0.137, implying that the parameter estimates are barely the same when a SUR estimation is performed.

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. We will return to the estimates of the monetary transmission mechanism in the next subsection with Figure 3.

Given the backward-looking nature of the problem, the derivation of the optimal policy rule in (5) relies on the assumption that the structure of the economy is invariant to monetary policy, and therefore it is subject to the Lucas critique (1976). However, we show below not only that the policy preference parameters are stable over the sample but also that the associated optimal path of interest rates displays substantial policy inertia and limited deviations from the estimated one. It follows that one may reasonably expect the behavioural parameters to be stable as well, thereby reducing the significance of the Lucas critique.[7]

It is important to stress the timing assumption of our model. At the beginning of each period t, the central bank observes all state variables up to time t included (i.e. the policy maker knows the value of the variables in the vector (4)). On the basis of those values the central bank sets the optimal policy rate. Then, nominal and real shocks hit the economy, so that at the beginning of period $t+1$ a new vector of state variables influences the central bank's decisions.

Hence, consistently with our set-up, we may exploit all the information available at time t to estimate by OLS the stochastic version of the optimal rule derived in (5). The estimates yield these results:

$$
\begin{aligned}
i_t = &\underset{(0.07)}{0.212}\,\pi_t + \underset{(0.08)}{0.043}\,\pi_{t-1} + \underset{(0.08)}{0.151}\,\pi_{t-2} - \underset{(0.09)}{0.177}\,\pi_{t-3} + \underset{(0.10)}{0.346}\,y_t + \\
&-\underset{(0.11)}{0.265}\,y_{t-1} + \underset{(0.14)}{1.259}\,i_{t-1} + \underset{(0.20)}{0.398}\,i_{t-2} - \underset{(0.12)}{0.008}\,i_{t-3} + \hat{v}_t
\end{aligned}
\tag{9}
$$

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

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

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

4.2. Greenspan's Policy Preferences

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

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

The optimal policy effectively captures the main features of funds rate movements under the Greenspan's chairmanship, although it predicts a higher level of interest rates both at the beginning and at the end of the sample. Since inflation is found to be the only final concern of the Fed and since it is affected by interest rates with two lags, we look at the relationship between forwarded inflation and current interest rates. Interestingly, a comparison between Figures 1 and 2 shows that, whenever observed policy rates are lower (higher) than those predicted by the optimal rule, inflation is high (low) and above (below) its target, which is zero by construction.[8] This seems to call for a time-varying inflation target over the sample. However, to be consistent with other empirical analyses, we keep a constant inflation target. Our findings line up with those in Sack (2000), although we use a different specification of the economic structure and, most importantly, a different set of policy preferences.

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

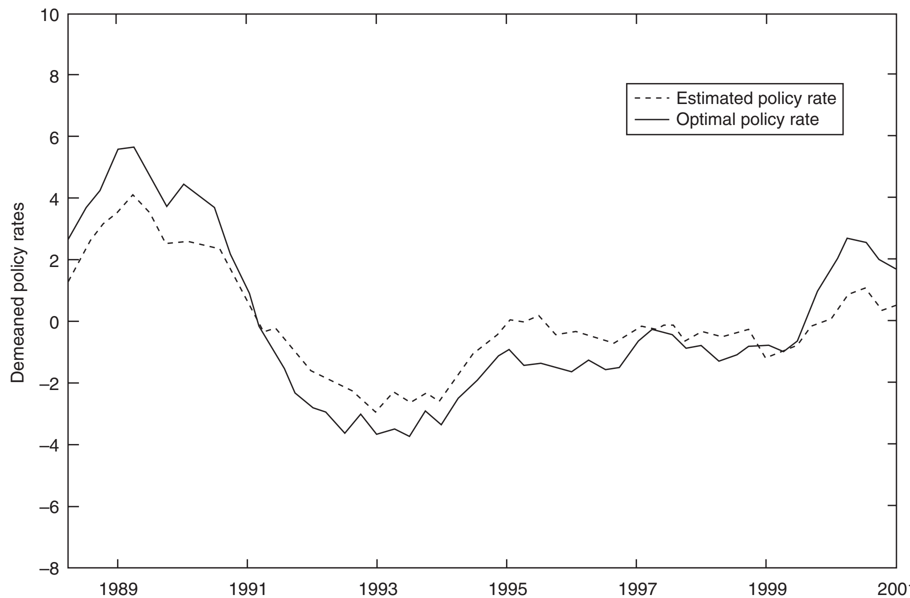

Figure 1: Estimated and Optimal Policy Rates

Note: The optimal policy rate is computed given the actual history of the economy at each point in time.

Figure 2: Actual Path of Inflation

The values of the preference parameters are not affected by imposing other values for the interest rate-smoothing weight, $\lambda_{\Delta i}$, since the value of λ_{π} turns out to be always the complement to one of any $\lambda_{\Delta i}$ value. Furthermore, the higher the preference parameter on inflation stabilization, the better is the match between optimal and fitted rates for any given value of the interest rate-smoothing coefficient. This suggests that the conduct of monetary policy in the US is successfully described by a *strict inflation targeting* as defined in Rudebusch and Svensson (2002) and Ball (1999), and according to which the stabilization of output around its potential value has not been a final concern of monetary authorities (i.e. $\lambda_y = 0.00$). However, we do not mean that the output gap has not been important in policy actions. Indeed, the feedback rule estimates show that it has been regarded as a leading indicator for future inflation rather than as a goal variable (i.e. it is an argument in the reaction function rather than in the loss). This finding is in line with those in Favero and Rovelli (2001), and Dennis (2001).

Interestingly, with our estimated system (7)–(8), together with the optimally computed feedback rule (5), it is possible to produce model-consistent impulse response functions.[9] Figure 3 shows dynamic responses very much in line with those provided by Christiano *et al.* (1998). In particular, after a positive demand shock, the central bank must open a negative output gap to tackle the inflationary pressure. By contrast, in response to a cost-push shock, monetary policy makers raise the short-term nominal interest rate, so depressing the real economy. This induces the inflation rate to be back on average to its target, although at the cost of periods of under-production. The volatile pattern shown by the inflation rate in both these cases may be due to the will of the central bank to target annual inflation. It should be noticed that because of the recursive nature of the CB's problem, the behaviour of monetary authorities, as captured by (5), influences the aggregate demand and the aggregate supply through movements in the real interest rate. In particular, Figure 3 shows that despite its statistical (in)significance, the parameter governing the monetary transmission mechanism, namely β_3, is indeed crucial to generate data-consistent impulse response functions.

4.3. *Sensitivity Analysis*

The calibration of the central bank's policy preferences relies on the assumption that the AD–AS system specified in (1) and (2) is actually the

[9] To produce impulse response functions, we feed the system (5), (7)–(8) with either a supply shock ϵ_1 or a demand shock u_1 (magnitudes: their standard deviations), and we let the system evolve accordingly without shocking it further. As our set-up is designed to study the systematic component of monetary policy, the central bank's reaction function can only be regarded as non-stochastic. However, the recursive impact of a change in the policy rate stemming from a change in the state variables can be gauged through the lagged effects of monetary policy on the structure of the economy.

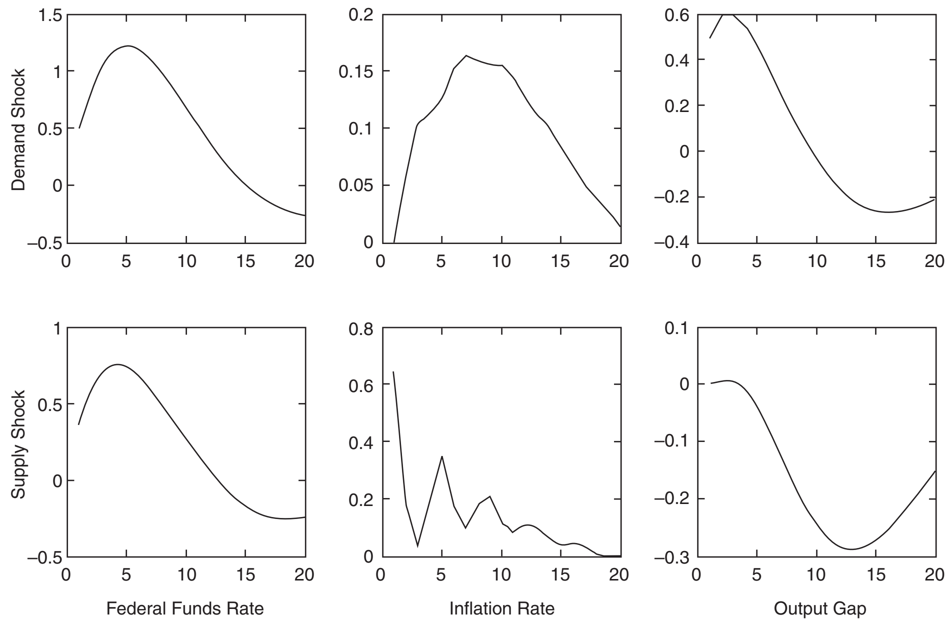

Figure 3: Model Consistent Impulse Response Functions

macroeconometric model that policy makers have in mind. Indeed, researchers are uncertain about what it is, along both the parameter and the model dimension. In particular, monetary authorities may use sub-sample windows to capture the changing of the economic structure or may employ a different dynamics specification of their empirical model. For this reason, we relax in turn the assumptions that both the behavioural parameters and the model specification are time-invariant so as to assess the robustness of our results. First, given the model (1)–(2), we perform rolling sub-sample estimates to identify the associated values of the US policy makers' preferences for five-year moving windows. The values that the inflation stabilization coefficient, λ_π, takes over time are plotted in Figure 4 for the benchmark case (i.e. $\lambda_{\Delta i} = 0.2$).

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

We turn our attention now to alternative specifications of the economic structure that might as well be relevant to monetary authorities. The goal is to identify of a set of policy preferences robust to model mis-specifications.[10] To this end, we apply our calibration method to a number of empirical models that display a reasonably good fit in a given class of specifications. This class comprises all combinations of a base set of eight regressors for the AS and nine for the AD whose richest specification takes the form:

$$\begin{aligned}\pi_{t+1} = {} & \alpha_1\pi_t + \alpha_2\pi_{t-1} + \alpha_3\pi_{t-2} + \alpha_4\pi_{t-3} \\ & + \alpha_5 y_t + \alpha_6 y_{t-1} + \alpha_7 y_{t-2} + \alpha_8 y_{t-3} + \xi_{t+1}\end{aligned} \tag{10}$$

$$\begin{aligned}y_{t+1} = {} & \beta_1 y_t + \beta_2 y_{t-1} + \beta_3 y_{t-2} + \beta_4 y_{t-3} + \beta_5\pi_t \\ & + \beta_6\pi_{t-1} + \beta_7\pi_{t-2} + \beta_8\pi_{t-3} + \beta_9(\bar{i}_t - \bar{\pi}_t) + \eta_{t+1}\end{aligned} \tag{11}$$

Among these, we first select and then combine the top ten AS with the top ten AD where the ranking is based on the Akaike model selection criterion. In 90 of 100 cases, a *strict inflation targeting* overperforms any other targeting strategy and not surprisingly the outliers are the specifications combining the alternative AS equations with the only 'theoretically implausible' AD, namely the one in which the aggregate demand positively depends on interest rate.

These findings are stable and robust to some form of model and parameter uncertainty, and therefore they appear to fairly describe the

[10] We stress that the source of uncertainty here is the unknown view that Greenspan has about the economy rather than the unknown 'true' dynamics of the world.

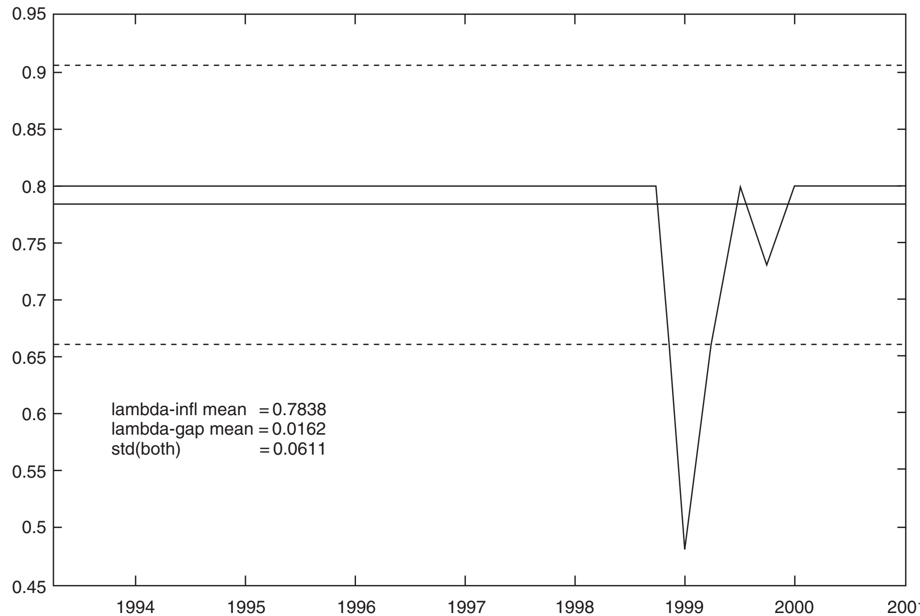

Figure 4: Preference Parameter on Inflation Stabilization over Time
Note: Each parameter estimate is obtained from a five-year rolling sub-sample regression that ends in the quarter in which the parameter estimate is plotted.

Fed policy preferences under Greenspan's chairmanship. Interestingly enough, Söderlind *et al.* (2002) and Castelnuovo (2003) use a hybrid model of the economy that allows for both forward-looking and backward-looking components, and find a very low value for the relative weight on output stabilization in the central bank's loss function. This suggests that the policy preferences we calibrate over Greenspan's tenure are robust to the assumption of how private agents form their expectations.

5. Conclusions

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

Our findings show that Greenspan's tenure 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. Indeed, the feedback estimates show that the output gap has been important in policy making. However, since it is found to enter the policy rule but not the objective function, it can only be interpreted as a leading indicator for future inflation. Furthermore, our results are pretty stable over Greenspan's era and particularly robust to alternative specifications of the relevant structure of the economy.

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Appendix: The Optimal Control Problem

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

$$E_t \sum_{\tau=0}^{\infty} \delta^{\tau} LOSS_{t+\tau} \tag{12}$$

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

$$LOSS_t = \lambda_{\pi}\bar{\pi}_t^2 + \lambda_y y_t^2 + \lambda_{\Delta i}(i_t - i_{t-1})^2 \tag{13}$$

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

When the discount factor, δ, approaches unity, the intertemporal loss function in (12) approaches the unconditional mean of the period loss function:

$$E[LOSS_t] = \lambda_\pi Var[\bar{\pi}_t] + \lambda_y Var\ [y_t] + \lambda_{\Delta i} Var[\Delta i_t] \tag{14}$$

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:

$$X_{t+1} = AX_t + Bi_t + \eta_{t+1} \tag{15}$$

where the elements of (15) are given by

$$X'_t = [\pi_t \quad \pi_{t-1} \quad \pi_{t-2} \quad \pi_{t-3} \quad y_t \quad y_{t-1} \quad i_{t-1} \quad i_{t-2} \quad i_{t-3}] \tag{16}$$

$$A = \begin{bmatrix} \alpha_1 & \alpha_2 & \alpha_3 & \alpha_4 & \alpha_5 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{-\beta_3}{4} & \frac{-\beta_3}{4} & \frac{-\beta_3}{4} & \frac{-\beta_3}{4} & \beta_1 & \beta_2 & \frac{\beta_3}{4} & \frac{\beta_3}{4} & \frac{\beta_3}{4} \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \quad B = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \frac{\beta_3}{4} \\ 0 \\ 1 \\ 0 \\ 0 \end{bmatrix} \tag{17}$$

$$\eta'_t = [\epsilon_t\ 0\ 0\ 0\ u_t\ 0\ 0\ 0\ 0] \tag{18}$$

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

The loss function in (13) can be represented in a more compact form by defining the 3×1 vector Y_t of goal variables. This vector reads

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

where the elements of (19) are given by

$$(20) \quad Y_t = \begin{bmatrix} \bar{\pi}_t \\ y_t \\ i_i - i_{t-1} \end{bmatrix} \; C = \begin{bmatrix} \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 \end{bmatrix} \; D = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

Accordingly, the loss function can be rewritten as

$$(21) \qquad LOSS_t = Y_t' R Y_t$$

where R is a 3×3 diagonal matrix, whose diagonal elements are the weights λ_π, λ_y and $\lambda_{\Delta i}$.

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

$$(22) \qquad \sum_{\tau=0}^{\infty} \delta^{\tau} \{ Y_{t+\tau}' R Y_{t+\tau} \}$$

subject to the dynamic evolution of the economy described in (15) and given the current state of the economy X_t.

The quadratic objective function, the linear transition equation and the property $E(\eta_{t+1}|X_t) = 0$ are convenient forms for the stochastic optimal linear regulator problem (Ljungqvist and Sargent, ch. 4, 2000). It follows that the feedback rule which solves the optimization is linear and independent from the problem's noise statistics, Φ, as the certainty equivalence holds. Then, the first-order necessary condition turns out to be

$$(23) \qquad (S + \delta B' P B) i = -(V' + \delta B' P A) X$$

which implies the following feedback rule for the policy instrument $i = fX$ where f is given by

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

The 9×9 matrix P is the solution of the algebraic Riccati equation

$$(24) \qquad P = Q + \delta (A + Bf)' P (A + Bf) + f' S f + V f + f' V'$$

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

Such a reaction function 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.

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

Non-technical Summary

Since the seminal article by John Taylor (1993), a burgeoning empirical literature has established interest rate rules as a convenient representation of central banks' behaviour. From a theoretical point of view, interest rate rules have been modelled as the solution of a constrained optimization problem where policy makers are in charge to stabilize some relevant macroeconomic aggregates around the assigned targets. According to this modelling, the policy rule coefficients must be interpreted as convolutions of the parameters describing central bank's preferences (i.e. the coefficients in the objective function) and the parameters framing the structure of the economy (i.e. the coefficients in the constraints). It follows that the estimates of an optimizing policy rule reflect a reduced form representation and, therefore, they cannot serve to study the structural features that identify a monetary regime.

By contrast, the policy preference parameters are informative on those structural features and they are worthy to estimate for three main reasons: first, to improve our understanding of policy actions because any decision can be more easily interpreted once the scope is identified; second, to assess the performance of monetary policy by establishing if the policy outcome is the pursued result of targeted policies rather than the random payoff of favourable macroeconomic conditions; and third, to carry out policy evaluations from the comparison between optimal and observed interest rates, as a sample-specific optimal rule can only be derived once the preference parameters are estimated over that sample.

Accordingly, we develop a calibration strategy to extract a central bank's preferences from the estimates of the reaction function that solves the policy makers' optimization problem. In particular, we select among a fairly wide class of alternative targeting policies the set of preference parameters that makes the associated optimal simulated path of policy rate closest to the estimated path. We apply our identification method to US data so as to identify the policy preferences of the Federal Reserve. Hence, we contribute to the recent literature pioneered by Favero and Rovelli (2001), Dennis (2001) and Cecchetti and Ehrmann (2001). While our purpose stands by those of previous studies, we take from them two important departures: first, we use a different sample, which is restricted to the single administration of Alan Greenspan, according to the reasoning that policy preferences are Chairman-specific; and second, we employ a different estimation method (i.e. calibration) with respect to those used by the authors listed above.

The empirical analysis shows that the stabilization of output over the cycle has not been a final concern of US monetary authorities, although policy rates have been set in response to both inflation and output gap. This implies that any deviation of output from its potential value has been regarded by the Fed as a leading indicator for future inflation, thus being only instrumental to stabilize inflation rather than important *per se*.