The Performance of Forecast-Based Monetary Policy Rules Under Model Uncertainty

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We investigate the performance of forecast-based monetary policy rules using five macroeconomic models that reflect a wide range of views on aggregate dynamics. We identify the key characteristics of rules that are robust to model uncertainty; such rules respond to the one-year-ahead inflation forecast and to the current output gap and incorporate a substantial degree of policy inertia. In contrast, rules with longer forecast horizons are less robust and are prone to generating indeterminacy. Finally, we identify a robust benchmark rule that performs very well in all five models over a wide range of policy preferences. (*JEL* E31, E52, E58, E61)

A number of industrialized countries have adopted explicit inflation forecast targeting regimes, in which the stance of policy is adjusted to ensure that the inflation rate is projected to return to target over a specified horizon.[1] Such a regime has also received formal consideration recently by the Bank of Japan, while Svensson (1999) and others have recommended that the Federal Reserve and the European Central Bank should follow suit.[2] In principle, forecast-based policies can incorporate comprehensive and up-to-date macroeconomic information and can account for transmission lags and other structural features of the economy. Furthermore, simple forecast-based policy rules may serve as useful benchmarks that facilitate public communication regarding monetary policy objectives and procedures.[3]

In analyzing forecast-based policies, researchers have generally proceeded by determining rules that yield optimal or near-optimal stabilization performance in a specific macroeconometric model.[4] However, given substan-

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[1] Leonardo Leiderman and Lars E. O. Svensson (1995), Ban S. Bernanke and Frederic S. Mishkin (1997), and Bernanke et al. (1999) provide extensive background on and analysis of inflation targeting regimes in Australia, Canada, Israel, New Zealand, Sweden, and the United Kingdom. Explicit inflation targeting has also been adopted by a substantial number of emerging market countries; see Andrea Schaechter et al. (2000).

[2] In particular, Svensson (1999), Svensson and Michael Woodford (1999), and Charles A. E. Goodhart (2000) recommend that central banks commit to an inflation forecast targeting rule.

[3] Menzi Chinn and Michael Dooley (1997), Richard Clarida and Mark Gertler (1997), Clarida et al. (1998), and Athanasios Orphanides (2001) have found that estimated forecast-based reaction functions provide reasonably accurate descriptions of interest rate behavior in Germany, Japan, and the United States during the 1980's and 1990's. Therefore, adopting an explicit forecast-based rule as a policy benchmark might primarily involve a change in the communication of policy and not necessarily a major shift in policy actions.

[4] Such research has been performed at the Reserve Bank of Australia (Gordon de Brouwer and Luci Ellis, 1998), the

tial uncertainty about the "true" structure of the economy (cf., Bennett McCallum, 1988, John B. Taylor, 1999a), it is essential to identify the characteristics of policy rules that perform well across a reasonably wide range of models; that is, to identify rules that are robust to model uncertainty.[5] This approach seems particularly important in analyzing forecast-based rules, since the performance of these rules is contingent on the accuracy of the forecasting model.

Thus, in this paper we investigate the performance and robustness of forecast-based rules using four structural macroeconometric models that have been estimated using postwar U.S. data, along with a small stylized model derived from microeconomic foundations with calibrated parameter values. All five models incorporate the assumptions of rational expectations, short-run nominal inertia, and long-run monetary neutrality. Nevertheless, these models exhibit substantial differences in price and output dynamics, reflecting ongoing theoretical and empirical controversies as well as differences in the degree of aggregation, estimation method, sample period, etc.

We assume that the policy maker makes a permanent commitment to follow a time-invariant rule, and that the policy maker's objective is to minimize a weighted sum of the unconditional variances of the inflation rate and the output gap, subject to an upper bound on nominal interest rate volatility.[6] We focus on simple instrument rules, in which the short-term nominal interest rate is adjusted in response to current or projected future values of the inflation rate and the output gap as well as to the lagged nominal interest rate. We begin by determining the conditions on the policy rule parameters (including the choice of forecast horizon) that are required to ensure a unique stationary rational expectations equilibrium in each model. Next we determine the optimal forecast horizons and other policy parameters that minimize the policy maker's loss function in each model, and we analyze the robustness of each optimized rule by evaluating its performance in each of the other models. Having identified a particular class of robust policy rules, we then determine the policy parameters that minimize the average loss function across all five models; from a Bayesian perspective, this approach corresponds to the case in which the policy maker has flat prior beliefs about the extent to which each model provides an accurate description of the true economy.

Our analysis concludes by identifying a specific forecast-based policy rule that can serve as a robust benchmark for monetary policy; this rule performs remarkably well for a wide range of policy preferences as well as for a wide range of prior beliefs about the dynamic properties of the economy. More generally, our results provide support for policy rules that respond to a short-horizon forecast (no more than one year ahead) of a smoothed measure of inflation, that incorporate a substantial response to the current output gap, and that involve a relatively high degree of policy inertia (also referred to as "interest rate smoothing").[7] We find that well-designed rules are highly robust to model uncertainty, particularly in contrast with the lack of robustness of rules that involve longer-horizon inflation forecasts or that omit an explicit response to the output gap.

Finally, it should be noted that our approach of evaluating the robustness of monetary policy rules to model uncertainty is complementary to Bayesian methods that analyze the policy implications of uncertainty about the parameters

Bank of Canada (Douglas Laxton et al., 1993; Richard Black et al., 1997b; Robert Amano et al., 1999), the Bank of England (Andrew Haldane, 1995; Nicoletta Batini and Haldane, 1999; Batini and Edward Nelson, 2001), and the Reserve Bank of New Zealand (Black et al., 1997a). Glenn D. Rudebusch and Svensson (1999) analyzed the performance of instrument and targeting rules in a small adaptive-expectations model of the U.S. economy.

[5] Monetary policy under model uncertainty has previously been analyzed by Elias Karakitsos and Berc Rustem (1984), Robin G. Becker et al. (1986), Jeffery A. Frankel and Katherine Rockett (1988), Gerald Holtham and Andrew Hughes-Hallett (1992), and Nico Christodoulakis et al. (1993). Most recently, Levin et al. (1999) evaluated the robustness to model uncertainty of optimized simple policy rules involving current and lagged macroeconomic variables, while Taylor (1999b) summarized the performance of five rules in an even wider range of macroeconomic models.

[6] For recent analysis of the monetary policy implications of time inconsistency and commitment vs. discretion, see Paul Söderlind (1999), Woodford (1999), Svensson (2001), Richard Dennis and Ulf Söderstrom (2002), and Svensson and Woodford (forthcoming).

[7] For analysis of interest rate smoothing in outcome-based rules, see Marvin Goodfriend (1991), Levin et al. (1999), Julio J. Rotemberg and Woodford (1999), Williams (1999), Woodford (1999), Brian Sack and Wieland (2000), and Woodford (2000).

of a particular model, as well as to robust control methods that indicate how to minimize the "worst-case" losses due to perturbations from a given model.[8] Unlike these other approaches, however, our method naturally lends itself to situations in which nonnested models represent competing perspectives regarding the dynamic structure of the economy.

The remainder of this paper proceeds as follows. Section I highlights the key issues regarding the specification of forecast-based policy rules. Section II provides a brief overview of the dynamic properties of the five macroeconomic models. In Section III, we analyze the restrictions on forecast-based rules that are required to ensure a unique rational expectations equilibrium. Section IV evaluates the specification and performance of forecast-based rules that are optimized for each individual model. Section V considers the extent to which these optimized rules are robust to model uncertainty and identifies the characteristics of robust policy rules. In Section VI, we find the policy parameters that minimize the average loss function across all five models, and then we identify a specific forecast-based rule that can serve as a benchmark for policy analysis. Section VII summarizes our conclusions and considers directions for further research.

I. Specification of Forecast-Based Policy Rules

In this section, we consider the choices involved in specifying a forecast-based monetary policy rule, in light of the theoretical arguments for these rules as well as the characteristics of various rules that have been considered in the literature.

One intuitively appealing argument for forecast-based rules is that monetary policy acts with a nontrivial lag, and hence current policy actions should be determined in light of the macroeconomic conditions that are expected to prevail when such actions will have a substantial effect. (This rationale is referred to as "lag encompassing" by Batini and Haldane, 1999.) Of course, since any forecast can be expressed in terms of current and lagged state variables, a forecast-based rule cannot yield any improvement in macroeconomic stability relative to the fully optimal policy rule (which incorporates all of the relevant state variables). However, a simple forecast-based policy rule might perform substantially better than a simple *outcome-based* (OB) rule (that is, a rule involving only a small set of current and lagged variables). For example, consider a sharp hike in import oil prices that gradually passes through to prices of domestically produced output: an outcome-based policy rule reacts only as the inflationary effects are realized, whereas a forecast-based rule can respond immediately to the shock and hence get a head start on restraining its inflationary effects.

A related argument (referred to as "information encompassing" by Batini and Haldane) is that forecast-based policy rules can implicitly incorporate a wide variety of information regarding the current state of the economy as well as anticipated future developments. For example, a forecast-based rule can automatically adjust the stance of monetary policy depending on whether a given macroeconomic disturbance is expected to persist or to vanish quickly. In contrast, a simple outcome-based rule prescribes a fixed policy response to a given movement in the inflation rate, regardless of whether the underlying shock is transitory or persistent. In principle, a forecast-based rule can incorporate an even wider array of information, because the forecast itself can embed judgmental adjustments that reflect idiosyncratic events beyond the scope of any particular macroeconometric model.

Finally, it has been argued that monetary policy can effectively stabilize both inflation and output through a rule that *only* involves inflation forecasts, with no explicit response to the output gap. (Batini and Haldane refer to this feature of forecast-based rules as "output encompassing.") In principle, the forecast horizon of the rule can be adjusted to reflect the policy maker's preferences for stabilizing output vs. inflation in response to aggregate supply shocks; that is, with a longer inflation forecast horizon, the policy rule brings inflation back to

[8] Optimal policy under parameter uncertainty was investigated in the seminal paper of William Brainard (1967) and was extended by the work of David Kendrick (1982) and others; recent examples include Ronald Balvers and Thomas Cosimano (1994) and Wieland (2000). Applications of robust control methods include Peter von zur Muehlen (1982), Marc P. Giannoni (2000), Lars P. Hansen and Thomas J. Sargent (2001), Robert Tetlow and von zur Muehlen (2001), and Alexei Onatski and James H. Stock (2002).

TABLE 1—CHARACTERISTICS OF FORECAST-BASED RULES FROM THE LITERATURE

General specification

$$i_t = \rho i_{t-1} + (1 - \rho)(r^* + E_t\tilde{\pi}_{t+\theta}) + \alpha(E_t\tilde{\pi}_{t+\theta} - \pi^*) + \beta E_t y_{t+\kappa}$$

Label	Source	θ	κ	ρ	α	β
Inflation forecast horizon ≤ 1 year						
A	Clarida et al. (2000)	4	0	0.84	0.27	0.09
B	Orphanides (2001)	4	4	0.56	0.27	0.36
C	de Brouwer and Ellis (1998)	4	4	0	2.80	1.00
D	Batini and Nelson (2001)	2	—	0.98	1.26	—
E	Peter Isard et al. (1999)	3–4	—	0	1.50	—
Inflation forecast horizon ≥ 2 year						
F	Rudebusch and Svensson (1999)	8	—	0.62	1.97	—
G	Rudebusch and Svensson (1999)	12	—	0.71	3.57	—
H	Batini and Nelson (2001)	15	—	0.85	34.85	—
I	Amano et al. (1999)	$i_t = i_t^b + 3.0(E_t\tilde{\pi}_{t+8} - \pi^*)$				
J	Batini and Haldane (1999)	$i_t = E_t\pi_{t+1} + 0.5r^* + 0.5(i_{t-1} - E_{t-1}\pi_t) + 0.5(E_t\pi_{t+8} - \pi^*)$				

Notes: Rules D, F, G, H, and J utilize the annualized one-quarter inflation rate (π) instead of the four-quarter average inflation rate ($\tilde{\pi}$). In rule E, the first inflation forecast (multiplied by the coefficient $1 - \rho$) uses a four-quarter horizon, while the second inflation forecast (multiplied by the coefficient α) uses a three-quarter horizon. The final two rules do not conform to the general specification: rule I involves the long-term nominal interest rate i_t^b, while rule J involves the lagged value of the *ex ante* real interest rate, $i_{t-1} - E_{t-1}\pi_t$.

target more gradually and thereby dampens the associated swings in output and employment.

In light of these considerations, it is helpful to review the characteristics of forecast-based rules that have been used in policy analysis at central banks as well as rules that have been studied by academic researchers. Ten such rules are characterized in Table 1. Rules A and B were fitted to U.S. data from the past two decades, while the remaining rules were determined based on their stabilization performance in specific macroeconometric models.[9] Five of these rules were obtained by analysts at the Bank of Canada, the Bank of England, and the Reserve Bank of Australia. As noted by Amano et al. (1999), rule I provides a good approximation to the reference rule used in the Bank of Canada's Quarterly Projection Model, a reference rule that has served as a rough benchmark but not the sole determinant of Canadian monetary policy.

Most of the rules in Table 1 can be expressed using the following general formulation:

$$(1) \quad i_t = \rho i_{t-1} + (1 - \rho)(r^* + E_t\tilde{\pi}_{t+\theta}) + \alpha(E_t\tilde{\pi}_{t+\theta} - \pi^*) + \beta E_t y_{t+\kappa},$$

where i denotes the short-term nominal interest rate, $\tilde{\pi}$ denotes the four-quarter average inflation rate, y denotes the output gap (the deviation of output from potential), r^* denotes the unconditional mean of the short-term real interest rate, and π^* denotes the inflation target; all of these variables are measured at annual rates in percentage points.[10] The operator E_t indicates the forecast of a particular variable, using information available in period t. The integers θ and κ denote the forecast horizons (measured in quarters) for inflation and the output gap, respectively.

Evidently, several important choices must be made in specifying a forecast-based rule. For example, the first five rules in Table 1 utilize a relatively short inflation forecast horizon (2–4 quarters), while the remaining rules use substantially longer horizons (8–15 quarters). (In all cases, the inflation forecast horizon equals or

[9] The parameters of rules C, D, E, I, and J were selected using models with rational expectations, while the parameters of rules F, G, and H were chosen based on performance in models with adaptive expectations.

[10] Levin et al. (2001) provide extensive results regarding the performance of rules involving the one-quarter annualized inflation rate instead of the four-quarter average inflation rate.

exceeds the output forecast horizon.) Seven of the ten rules reflect the "output encompassing" hypothesis described above and hence omit any explicit response to the output gap. Finally, a majority of the rules exhibit "interest rate smoothing" or "policy inertia"; that is, these rules involve a direct response to the lagged short-term interest rate.

Our subsequent analysis will consider the stabilization properties of rules of the form given in equation (1); these rules fall into the class of forecast-based *instrument* rules, in which the short-term nominal interest rate responds directly to a model-consistent forecast of the inflation rate and may also respond to the output gap and lagged interest rate. Nevertheless, as emphasized by Svensson (2001), such rules may be particularly susceptible to time-inconsistency problems. Thus, in future research it will be useful to analyze the robustness of forecast-based *targeting* rules, in which the policy instrument is determined by the first-order conditions of an explicit optimization of the central bank's objective function (cf., Svensson, 1997; Svensson and Woodford, 1999).[11]

II. The Five Models

In evaluating the performance of forecast-based monetary policy rules, we consider five different models of the U.S. economy. The first model is small and highly stylized; as in Bernanke and Woodford (1997), Clarida et al. (1999), and Woodford (forthcoming), this model consists of two equations derived from the behavior of optimizing agents:

$$\pi_t = \delta E_t \pi_{t+1} + \phi y_t + \varepsilon_t, \tag{2}$$

$$y_t = E_t y_{t+1} - \sigma(i_t - E_t \pi_{t+1} - r_t^*). \tag{3}$$

The price-setting equation (2) can be viewed as determining aggregate supply, while aggregate demand is determined by the "expectational IS curve" in equation (3) combined with a particular interest rate rule. Thus, in the subsequent discussion we refer to this model as the "optimizing AD-AS" model.[12]

While each of the four macroeconometric models has been fitted to U.S. data, the dynamic properties of these models exhibit marked differences that reflect ongoing theoretical and empirical controversies. In particular, the Fuhrer-Moore (FM) model exhibits the highest degree of inertia with respect to both aggregate demand and inflation (cf., Jeffrey C. Fuhrer and George Moore, 1995). In the Federal Reserve Board (FRB) model, prices and spending are subject to higher-order adjustment costs; this model also features a relatively detailed representation of the supply side of the economy (cf., Flint Brayton et al., 1997; David Reifschneider et al., 1999). In the multicountry model of Taylor (1993)—hereafter referred to as TMCM—prices are determined by staggered wage contracts, while consumption and investment expenditures are explicitly forward-looking and exhibit relatively little intrinsic inertia. Finally, the Monetary Studies Research (MSR) model developed by Orphanides and Wieland (1998) exhibits output dynamics similar to that of TMCM and inflation dynamics similar to that of the FM model.

To compare the properties of these models, we utilize an estimated federal funds rate equation as a benchmark policy rule. In particular, using U.S. quarterly data for the period 1980:1–1998:4, we estimated the following equation via two-stage least squares:

$$i_t = \underset{(0.31)}{-0.28} + \underset{(0.06)}{0.76} i_{t-1} + \underset{(0.11)}{0.60} \tilde{\pi}_t + \underset{(0.25)}{0.21} y_t + \underset{(0.23)}{0.97} \Delta y_t. \tag{4}$$

[11] Note that in models with adaptive expectations, an alternative approach is to formulate policy in terms of an inflation forecast that is constructed using an unchanged nominal interest rate (cf., Rudebusch and Svensson, 1999; Per Jansson and Anders Vredin, 2001); however, researchers have varying opinions about how to implement and interpret this approach in models with rational expectations.

[12] In calibrating the model, we use the parameter values given in Woodford (forthcoming), simply adjusting these values to account for the fact that our variables are expressed at annual rates. Thus, we set $\delta = 0.99$, $\sigma = 1.59$, and $\phi = 0.096$, while r_t^* follows an AR(1) process with autocorrelation parameter 0.35, and the innovation is independently and identically distributed (i.i.d.) with a standard deviation of 3.72. We assume that the aggregate supply disturbance ε_t is i.i.d. and calibrate its standard deviation so that the unconditional variance of inflation under the benchmark estimated policy rule matches the sample variance of U.S. quarterly inflation over the period 1983:1–1999:4.

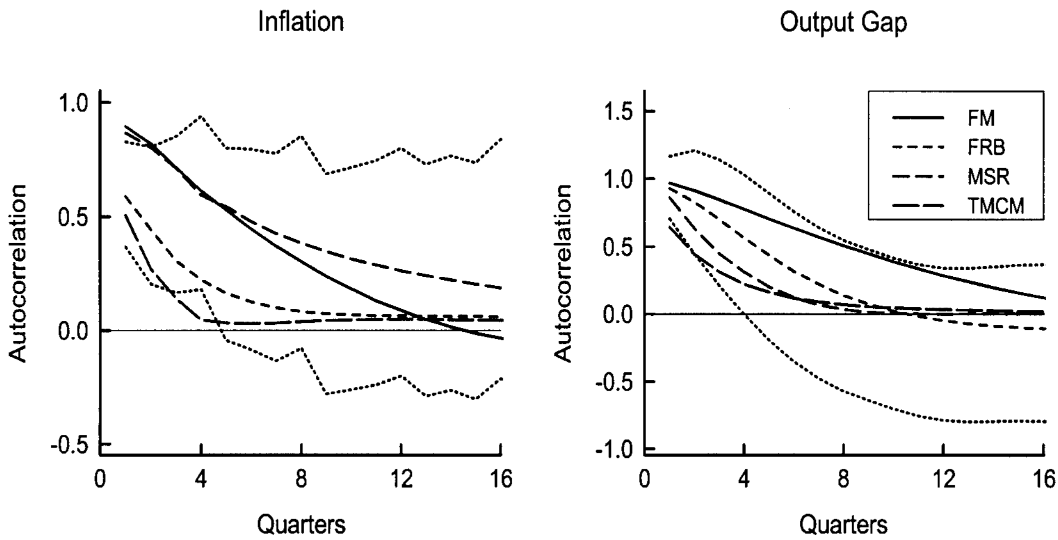

FIGURE 1. UNCONDITIONAL AUTOCORRELATIONS IN THE FOUR MACROECONOMETRIC MODELS

Note: The dotted lines indicate the upper and lower bounds of the 95-percent confidence interval for the sample autocorrelogram of each series (not shown), estimated over the period 1983–2000.

The standard error of each regression coefficient is given in parentheses.[13] Using this benchmark policy rule, we compute the unique stationary rational expectations solution of each model and then analyze its unconditional second moments and other dynamic properties.[14]

A measure of the degree of intrinsic persistence of the four macroeconometric models is provided by Figure 1, which shows the unconditional autocorrelations of inflation and the output gap.[15] Given that each macroeconometric model has been fitted to essentially the same data (apart from differences in sample period), it is not surprising that the implied autocorrelograms of all four models fall almost entirely within the empirical 95-percent confidence bands. Nevertheless, the fact that the correlograms of all four models are largely consistent with the data is really a reflection of the degree of sampling uncertainty: inflation is highly persistent in the FM and MSR models and far less so in the FRB and TMCM models, and the output gap is also much more persistent in the FM model than in the other three macroeconometric models.

The monetary transmission lags also differ substantially across the four macroeconometric models. Figure 2 shows the response of output and inflation in each model to a 100 basis point innovation to the benchmark policy rule. The peak output response occurs with a lag of one to four quarters, while the peak inflation response exhibits a lag of three to nine quarters. For comparison, it is interesting to note that estimated VAR models of the U.S. economy exhibit a monetary transmission lag of about two years for output and a lag of about three years for inflation (cf., Lawrence J. Christiano et al., 1996; Brayton et al., 1997).

[13] In estimating this equation, we used the quarterly average federal funds rate, the Congressional Budget Office (CBO) output gap series, and the inflation rate of the chain-weighted GDP price deflator. It should be noted that the rule also includes an economically and statistically significant response to the *change* in the output gap.

[14] The solution is obtained using the Gary Anderson and Moore (1985) implementation of the Olivier J. Blanchard and Charles M. Kahn (1980) method, modified to take advantage of sparse matrix functions.

[15] Autocorrelations provide a reasonable measure of intrinsic persistence for these four models because nearly all the shocks used for computing unconditional moments are serially uncorrelated; the only exceptions are the term premium shocks for certain financial variables in FRB and TMCM.

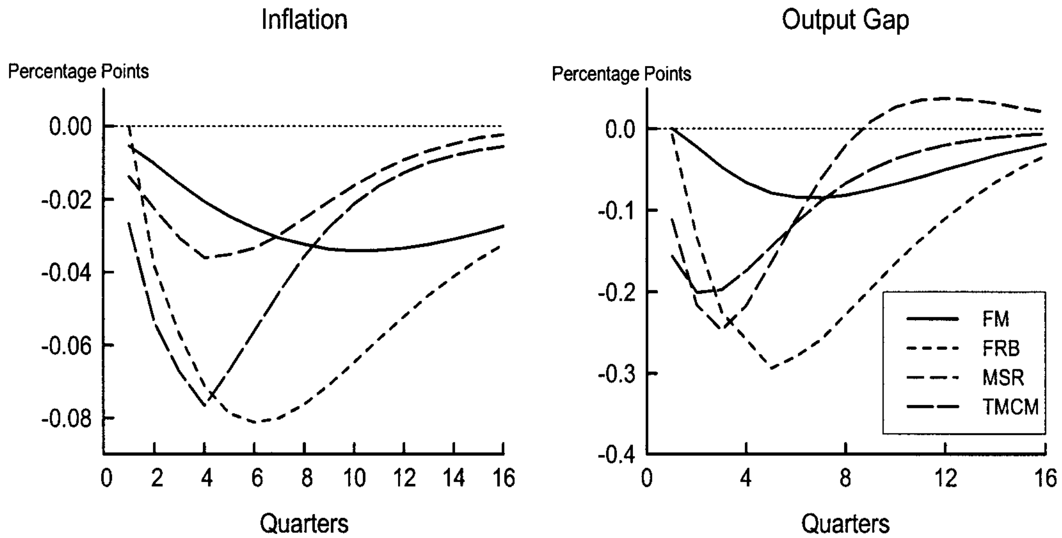

FIGURE 2. IMPULSE RESPONSES TO POLICY RULE INNOVATIONS

Note: The lines indicate the model responses to a 100 basis point innovation to the federal funds rate where policy is assumed to follow the benchmark rule given in equation (4).

III. Conditions for Determinacy

In analyzing the performance of forecast-based rules, we focus on the set of rules that yield a unique stationary rational expectations equilibrium in each model. If a rule fails to ensure determinacy, then the economy may follow a number of different equilibrium paths involving macroeconomic fluctuations that are unrelated to economic fundamentals; thus, such rules may be viewed as inherently undesirable.[16] We note that this view is not without controversy, and McCallum (1999) argues that the concern over multiple equilibria of the type that we study is misplaced.[17]

For the small stylized model, determinacy conditions can be obtained analytically for policy rules involving the one-step-ahead inflation forecast (cf., Bernanke and Woodford, 1997, and Woodford, forthcoming). In particular, determinacy not only places a lower bound on the value of α (a fairly standard condition for determinacy of policy rules in a wide range of macroeconomic models), but also imposes an upper bound on this coefficient. With a moderate policy response to expected inflation, there exists a unique stationary equilibrium; that is, any other values of the current output gap and current inflation rate are associated with an explosive path in subsequent periods. In contrast, with a sufficiently aggressive policy response to expected inflation, the output gap and inflation rate are projected to converge back to the steady state *regardless* of their values in the current period. Thus, at any given point in time, the output gap and the inflation rate can suddenly move in response to random shocks that are unrelated to economic fundamentals (often referred to as "sunspots"). Finally, these analytic conditions reveal that the link between expected and actual inflation is strengthened by an explicit response to the current output gap and/or the lagged nominal interest rate, and hence such rules are noticeably less susceptible to indeterminacy.

With longer forecast horizons or more complicated structural dynamics, analytical descriptions of the requirements for determinacy are not easily obtained. Therefore we now proceed to compute these conditions numerically for each of the five macroeconomic models. These results indicate that the issue of indeterminacy

[16] For recent analysis of this issue, see William Kerr and Robert G. King (1996), Bernanke and Woodford (1997), Christiano and Christopher Gust (1999), Clarida et al. (1999), and Woodford (forthcoming).

[17] See also McCallum (2001a).

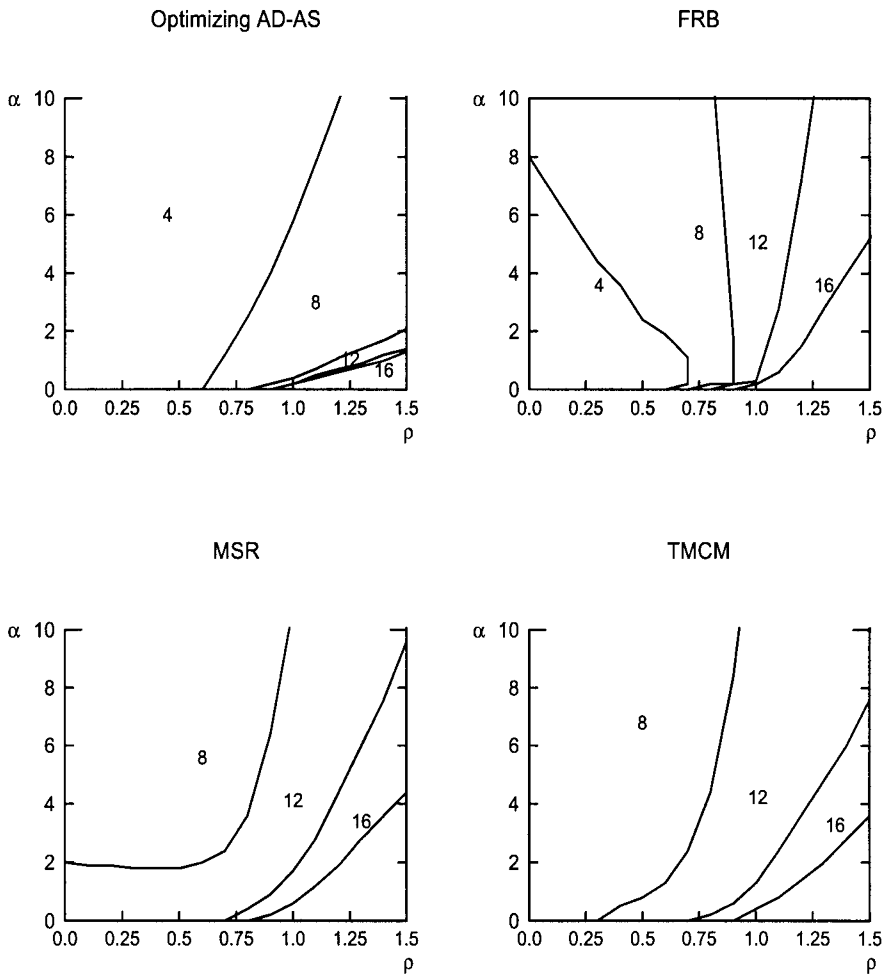

FIGURE 3. CROSS-MODEL COMPARISON OF INDETERMINACY REGIONS: $\beta = 0$

Notes: For each specification of the inflation forecast horizon (4, 8, 12, and 16 quarters), multiple equilibria occur for all combinations of the parameters α and ρ that lie to the northwest of the corresponding curve. If no curve is shown for a particular forecast horizon, then that specification yields determinacy for all combinations of $0 \leq \alpha \leq 10$ and $0 \leq \rho \leq 1.5$.

is relevant not only in small "stylized" models but also in macroeconometric models that exhibit a higher degree of inflation and output persistence. In fact, only the FM model is relatively immune to indeterminacy problems: due to its high degree of intrinsic persistence, this model exhibits very strong links between the current inflation rate and its expected value at horizons of up to four years.[18] In contrast, the determinacy conditions for the FRB, MSR, and TMCM models are qualitatively similar to those of the small stylized model; quantitatively, these conditions depend on the specific output and price dynamics of each model.

Figure 3 shows the indeterminacy boundaries for forecast-based rules that do not respond directly to the output gap. For each specification of the inflation forecast horizon, the corresponding

[18] Even with a forecast horizon of 16 quarters and no explicit response to the output gap, all combinations of $0 < \alpha \leq 10$ and $0 \leq \rho \leq 1.5$ are consistent with a unique rational expectations equilibrium in the FM model.

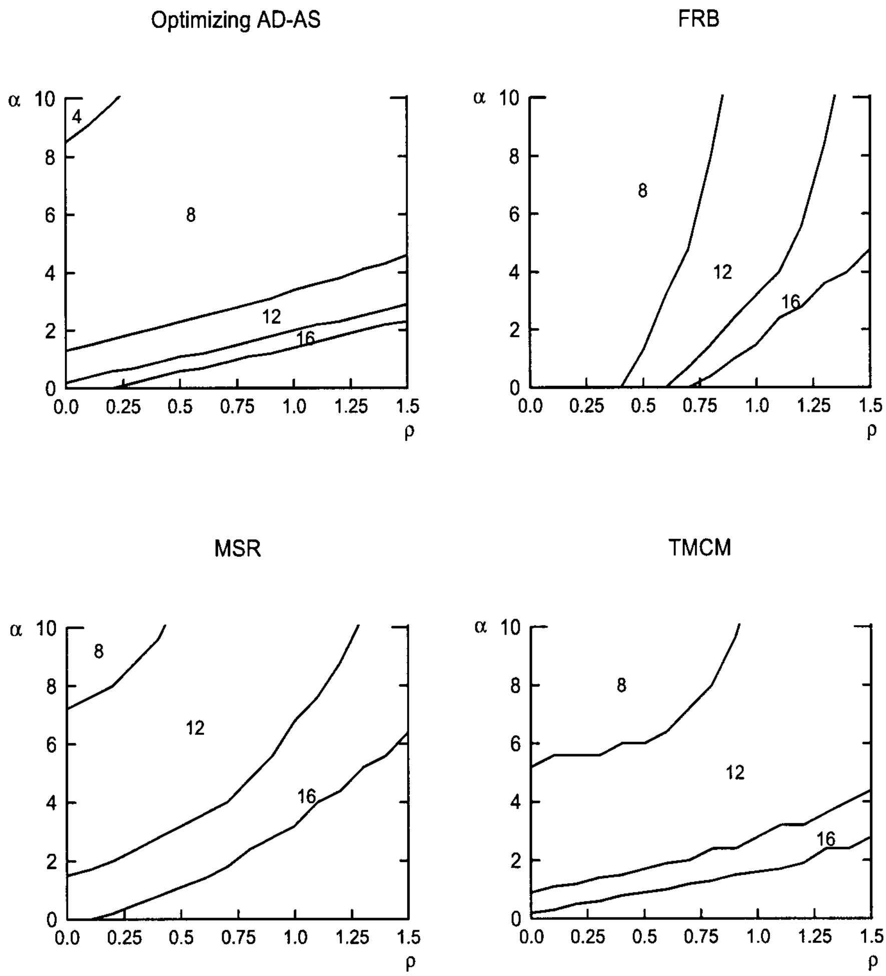

FIGURE 4. CROSS-MODEL COMPARISON OF INDETERMINACY REGIONS: $\beta = 1$

Note: See notes to Figure 3.

curve indicates the boundary of the indeterminacy region; that is, multiple equilibria occur for all combinations of the parameters α and ρ that lie to the northwest of the specified boundary. Evidently, the indeterminacy region expands with the length of the inflation forecast horizon and shrinks with the degree of interest rate smoothing. For example, an inflation forecast horizon of 16 quarters generates multiple equilibria for virtually all combinations of $0 < \alpha \leq 10$ and $0 \leq \rho \leq 1.5$. For rules involving a four-quarter inflation forecast horizon, determinacy occurs in the MSR and TMCM models for all combinations of α and ρ shown in the figure; in the FRB model, $\rho > 0.75$ is sufficient to ensure determinacy for all $0 < \alpha \leq 10$.[19]

Allowing for a moderate response to the current output gap shrinks the region of indeterminacy in each macroeconometric model. Figure 4 shows the indeterminacy boundaries for rules with a unit coefficient on the current output gap

[19] Although not shown in Figures 3 and 4, indeterminacy arises in each of the macroeconometric models if α is very close to zero, especially with long forecast horizons; this lower bound is typically on the order of 0.1.

TABLE 2—DETERMINACY OF RULES FROM THE LITERATURE

	Model				
Rule	Optimizing AD-AS	FM	FRB	MSR	TMCM
A	—	—	—	—	—
B	ME	—	—	—	—
C	ME	—	—	—	—
D	—	—	—	—	—
E	ME	—	ME	—	—
F	ME	—	ME	ME	—
G	ME	—	ME	ME	—
H	ME	ME	ME	ME	ME
I	ME	—	ME	ME	ME
J	ME	—	ME	—	—

Note: "ME" signifies that the rule yields multiple equilibria in the specified model, while "—" indicates that the rule yields a unique stationary equilibrium.

(that is, $\beta = 1$).[20] With this output response, rules with a four-quarter inflation forecast horizon yield a unique equilibrium in every model for every combination of $0 < \alpha \leq 8$ and $0 \leq \rho \leq 1.5$.

Our analysis highlights several key characteristics of rules that yield a unique equilibrium in every model, namely, a relatively short inflation forecast horizon, a moderate degree of responsiveness to the inflation forecast, an explicit response to the current output gap, and a substantial degree of policy inertia. In light of these results, it is interesting to check the determinacy properties of the rules taken from the literature, whose characteristics were discussed in Section I. Table 2 indicates whether each rule generates multiple equilibria ("ME") or determinacy ("—") in each of the five macroeconomic models.

Only rules A and D yield determinacy in every model. Rule A possesses all the characteristics supportive of determinacy, including the use of a four-quarter inflation forecast horizon, a positive output gap response, and a substantial degree of policy inertia. While rule D does not respond explicitly to the output gap, this rule uses a short inflation forecast horizon (only two quarters) and a high degree of policy inertia. Rules E through J generate multiple equilibria in at least two models; it is notable that none of these rules includes an explicit response to the output gap. Furthermore, five of these six rules have a relatively long inflation forecast horizon (at least eight quarters); the only exception is rule F, which has a shorter forecast horizon but suffers from a complete lack of policy inertia. Finally, rule H is unique in generating indeterminacy in the FM model (the model with the greatest degree of intrinsic inertia); this rule prescribes an exceptionally aggressive response to the 15-quarter-ahead inflation forecast.

[20] We have explored these indeterminacy regions for other values of β and obtained qualitatively similar results.

IV. Optimized Forecast-Based Rules

In this section, we investigate the characteristics of optimized forecast-based rules. For a given model and a specific form of the policy rule, we determine the inflation and output gap forecast horizons and coefficients that minimize a weighted average of inflation variability and output gap variability, subject to an upper bound on interest rate variability. Henceforth we shall restrict our attention to rules that yield a unique rational expectations equilibrium in the specified model. However, this restriction is almost never binding, in the sense that the optimal rules we consider are well away from the regions of indeterminacy shown in the previous section. (In the few cases where the constraint is binding, we will make note of that fact.)

A. *The Optimization Problem*

We assume that the policy maker's loss function $\mathcal{L}$ has the form

$$\mathcal{L} = \text{Var}(\pi) + \lambda \text{ Var}(y), \tag{5}$$

where Var(·) denotes the unconditional variance and the weight $\lambda \geq 0$ indicates the policy maker's preference for reducing output variability relative to inflation variability. This form of loss function has been used in many previous analyses, e.g., Taylor (1979), and can be derived using the same microeconomic foundations as those used to obtain the optimizing AD-AS model (cf., Woodford, forthcoming).[21] Mervyn

[21] The social welfare function involves additional terms if the model involves overlapping wage contracts (Christopher J. Erceg et al., 2000) or habit persistence in consumption (Fuhrer, 2000; Jeffery D. Amato and Laubach, 2001).

King (1997) refers to a policy maker who places no weight on output stability ($\lambda = 0$) as an "inflation nutter." In models with microeconomic foundations, the magnitude of the implied value of λ is very sensitive to the particular specification of overlapping nominal contracts: random-duration "Calvo-style" contracts imply that $\lambda \approx 0.01$ (Woodford, forthcoming), whereas fixed-duration "Taylor-style" contracts imply that $\lambda \approx 1$ (Erceg and Levin, 2001). Since the appropriate value of λ remains controversial, we will consider four different values, namely, 0, ⅓, 1, and 3.

For a given value of λ and a particular functional form of the policy rule, the parameters of the rule are chosen to minimize the loss function $\mathcal{L}$ subject to an upper bound on the volatility of changes in the short-term nominal interest rate; that is, the unconditional standard deviation of Δi_t cannot exceed a specified value $\bar{\sigma}_{\Delta i}$.

Henceforth we consider linear policy rules of the general form given by equation (1).[22] We also consider the more restricted class of rules that exclude an explicit output gap response (that is, $\beta \equiv 0$). Finally, we refer to outcome-based rules (in which the forecast horizons $\theta = \kappa = 0$) as the class of OB rules.

All five models considered in this paper exhibit a trade-off between inflation-output variability and interest rate variability, except at very high levels of interest rate variability.[23] Figure 5 illustrates this trade-off for the four macroeconometric models for three values of the policy preference parameter λ. In particular, for each model, we consider the set of OB rules of the form given by equation (1) for which the coefficients ρ, α, and β are chosen optimally given that the forecast horizons $\theta = \kappa = 0$. For a specific value of λ, each point on the corresponding curve indicates the minimized value of the loss function $\mathcal{L}$ for a particular value of $\bar{\sigma}_{\Delta i}$. The vertical line in each panel indicates the standard deviation of interest rate changes associated with the estimated benchmark rule given in equation (4); this interest rate volatility varies noticeably across the four models, mainly due to the use of a different sample period in estimating the parameters and the innovation covariance matrix of each model.

From Figure 5 it is evident that stabilization performance deteriorates rapidly if interest rate volatility is constrained to be much lower than that induced by the benchmark rule (which was estimated over the period 1980–1998). On the other hand, stabilization performance cannot be substantially improved even if interest rate volatility is permitted to be much higher than that induced by this rule (unless the policy maker places implausibly high weight on output volatility).[24] Therefore, we focus our attention on policy rules for which the parameters are chosen to minimize the loss function $\mathcal{L}$ subject to the constraint that interest rate volatility cannot exceed that of the estimated benchmark rule. The shadow value of this constraint, $\partial \log \mathcal{L}/\partial \bar{\sigma}_{\Delta I}$, is very small in all five models. For example, the shadow value in the AD-AS model (in percentage points) is 0.3, 0.3, 0.6, and 1.1 for $\lambda = 0$, ⅓, 1, and 3, respectively. For the four macroeconometric models, the shadow value never exceeds 0.4 for this range of values of λ.

B. *Characteristics of Optimized Rules*

We now analyze the optimal choices of forecast horizons and policy rule coefficients for each model for a range of values of the preference parameter λ. In particular, we consider a

[22] Given the assumption of a quadratic objective function and the linear structure of each model, the restriction to linear rules is innocuous and greatly facilitates computation. More generally, nonquadratic preferences or model nonlinearities give rise to nonlinear optimal policy rules. For example, explicit inflation targeting regimes typically are implemented with respect to a target zone rather than a specific target point, implying a nonlinear policy response (cf., Orphanides and Wieland, 2000a; Tetlow, 2000). In the present paper, we do not investigate the extent to which nonlinear policy rules are sensitive to model uncertainty, but rather leave this issue for future research.

[23] This trade-off is characteristic of many macroeconomic models in the recent literature; cf., the papers in Taylor (1999c), and further discussion in Sack and Wieland (2000).

[24] We also note that a linear policy rule which induces highly variable nominal interest rates may not be implementable in practice, because such a rule will prescribe frequent (and occasionally large) violations of the nonnegativity constraint on the federal funds rate (cf., Rotemberg and Woodford, 1999). In principle, we could analyze nonlinear rules that incorporate this nonnegativity constraint (see Fuhrer and Brian Madigan, 1997; Orphanides and Wieland, 1998, 2000b; Alexander L. Wolman, 1998; and Reifschneider and Williams, 2000), but doing so would substantially increase the computational costs of our analysis.

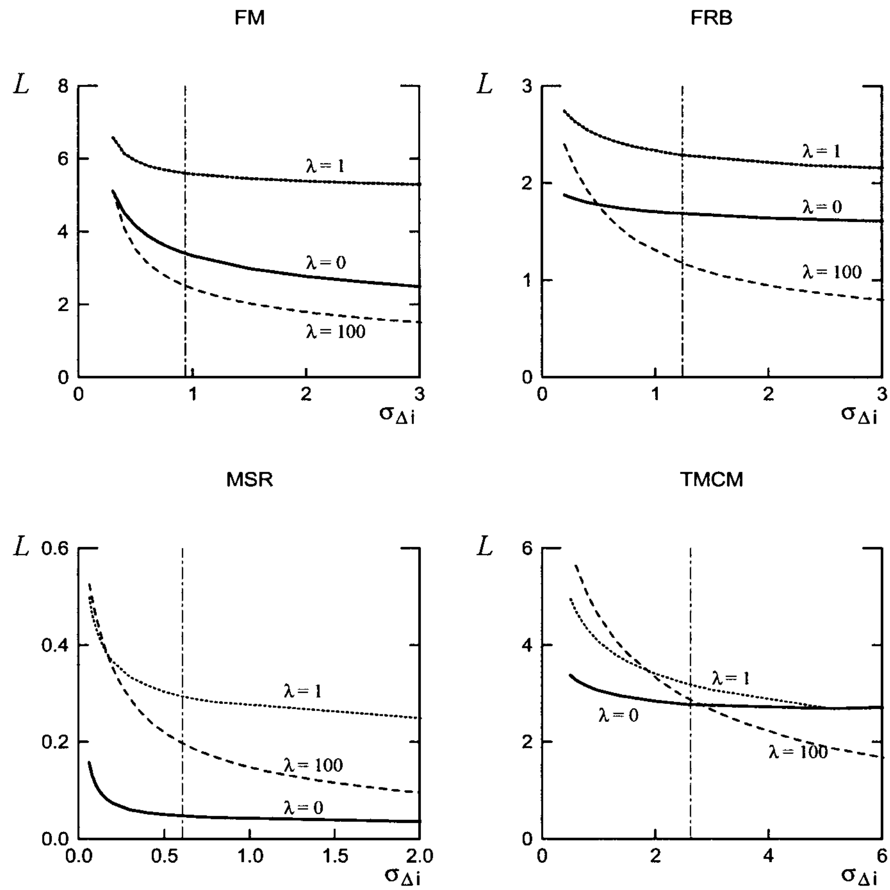

FIGURE 5. THE TRADE-OFF BETWEEN INTEREST RATE VARIABILITY AND MACROECONOMIC STABILIZATION

Note: The vertical dash-dot line indicates the value of $\sigma_{\Delta i}$ generated by the benchmark rule given by equation (4).

relatively large grid of possible combinations of inflation and output forecast horizons. For each point on this grid, we compute the values of the policy rule coefficients that minimize the loss function $\mathcal{L}$ subject to the specified upper bound on interest rate volatility. Finally, we compare the resulting values of $\mathcal{L}$ across the forecast horizon grid to determine the optimal combination of inflation and output forecast horizons. We only consider forecast horizons up to 20 quarters for both the inflation rate and the output gap; however, this constraint binds only in one case noted below.

For each model and each value of λ, Table 3 indicates the optimal forecast horizons for the inflation rate and output gap (θ and κ, respectively) and the optimal values of the three coefficients (ρ, α, and β). For example, most of these rules involve a very high degree of interest rate smoothing, roughly similar to that of the optimized outcome-based rules obtained by Levin et al. (2001) and Rotemberg and Woodford (1999).[25] This table also indicates the percent change in the loss function—denoted $\%\Delta\mathcal{L}$—generated by the forecast-based rule relative to that of the optimized OB rule. Note that $\%\Delta\mathcal{L}$ is always nonpositive, because the class of OB rules (for which $\theta = \kappa = 0$) is nested within the class of forecast-based rules.

For all five models, the optimal forecast horizons are generally very short, and never exceed four quarters. Furthermore, it is evident

[25] Woodford (1999) refers to rules with $\rho > 1$ as "super-inertial."

TABLE 3—CHARACTERISTICS AND PERFORMANCE OF OPTIMIZED RULES

Model	λ	θ	κ	ρ	α	β	$\%\Delta\mathcal{L}$
Optimizing	0	0	1	0.78	16.55	−0.64	−20
AD-AS	⅓	0	0	1.57	7.27	6.12	0
	1	0	0	1.55	3.04	6.23	0
	3	0	0	1.55	1.49	6.26	0
FM	0	1	0	0.96	0.51	0.10	0
	⅓	0	4	0.97	0.86	0.68	−1
	1	0	4	1.00	0.67	0.98	−1
	3	0	4	1.02	0.43	1.12	−1
FRB	0	4	1	1.28	5.47	0.02	−10
	⅓	0	2	1.16	1.63	1.46	−5
	1	0	2	1.19	1.21	1.97	−7
	3	0	2	1.19	0.74	2.16	−9
MSR	0	0	0	0.96	4.14	0.02	0
	⅓	0	1	1.25	2.91	1.92	−3
	1	0	1	1.22	1.71	2.01	−3
	3	0	1	1.19	0.99	2.03	−1
TMCM	0	2	0	1.04	3.59	0.11	−4
	⅓	2	0	0.97	1.33	1.28	0
	1	1	1	1.31	1.52	4.93	0
	3	1	1	1.33	0.85	5.10	−1

Notes: For each model and each value of the preference parameter λ, this table indicates the optimal forecast horizons for inflation and the output gap (θ and κ, respectively) and the optimal coefficient values (ρ, α, and β). The table also indicates the percent change in the policy maker's loss function ($\%\Delta\mathcal{L}$) generated by the rule relative to the optimized outcome-based rule.

that forecast-based rules *never* yield dramatic improvements in stabilization performance relative to simple outcome-based rules. The reduction in the policy maker's loss function is no more than 20 percent in all cases, and does not exceed 5 percent for every value of λ in three of the models (FM, MSR, and TMCM). Furthermore, while not shown in the table, we have confirmed that these results are not sensitive to the choice of inflation measure (four-quarter average vs. one-quarter annualized rate) or to the particular value of the upper bound on interest rate variability.[26]

Evidently, some of the purported advantages of forecast-based rules (such as "lag encompassing" and "information encompassing") are quantitatively unimportant, even in rational expectations models with substantial transmission lags and complex dynamic properties. These results are consistent with those of Levin et al. (1999), who found that fairly complicated outcome-based rules (which respond to a large number of observable state variables) yield only small stabilization gains over simple outcome-based rules. It is also interesting to note that Rudebusch and Svensson (1999) found similar results in a small macroeconometric model with adaptive expectations: although the Rudebusch-Svensson model includes a dozen state variables, the current output gap and four-quarter average inflation rate essentially serve as sufficient statistics for monetary policy, and hence forecast-based rules provide minimal stabilization gains even in that model.[27]

Finally, we consider optimized rules that do not respond explicitly to the output gap (that is, $\beta \equiv 0$); the characteristics and stabilization performance of these rules are indicated in Table 4. Evidently, the optimal inflation forecast horizon is considerably longer than for rules with an unconstrained output gap response. For example, with $\lambda = 1$, the optimal inflation forecast horizon is 8 quarters for the FRB model and 18 quarters for the FM model.[28]

As noted in Section II, some authors have argued that a rule which responds exclusively to the inflation forecast (with a suitable choice of forecast horizon) can be effective at stabilizing both output and inflation, even without an explicit response to the output gap. However, our results indicate that excluding the output gap from the policy rule may cause a severe deterioration in stabilization performance, at least when the policy maker places nontrivial weight on output stability. For example, when $\lambda = 1/3$, these rules generate excess losses (compared with OB rules) of over 100 percent in the FRB and MSR models and over 700 percent in the optimizing AD-AS model. Thus, "output en-

[26] We have repeated the analysis described above using an upper bound $\bar{\sigma}_{\Delta i}$ that is twice as large as the value associated with the estimated benchmark rule. Relaxing this constraint yields small improvements in stabilization performance, but the relative performance of forecast-based to outcome-based policy rules does not change significantly.

[27] Of course, such model-based evaluations do not reflect the potential benefits of responding to an inflation forecast that incorporates additional information via add factors and judgmental adjustments.

[28] As noted above, we restricted our search to forecast horizons up to 20 quarters; this bound is only reached in one case, namely, the inflation forecast horizon for the FM model when $\lambda = 3$.

TABLE 4—RULES WITH NO EXPLICIT OUTPUT GAP RESPONSE

Model	λ	θ	ρ	α	$\%\Delta\mathcal{L}$
Optimizing AD-AS	0	0	1.57	51.46	0
	⅓	2	−0.42	8.80	734
	1	2	−0.42	8.90	2,721
	3	2	−0.47	8.34	3,216
FM	0	9	1.21	2.55	1
	⅓	18	1.28	20.29	2
	1	18	0.77	4.60	11
	3	20	0.62	3.47	30
FRB	0	4	1.27	5.45	−10
	⅓	7	0.96	7.41	167
	1	8	0.94	8.70	407
	3	8	0.93	8.47	793
MSR	0	0	0.95	3.90	0
	⅓	5	−0.06	3.11	117
	1	4	−0.38	1.79	195
	3	4	−0.52	1.14	295
TMCM	0	3	1.14	4.92	−4
	⅓	3	0.73	3.41	24
	1	3	0.58	3.02	55
	3	6	0.50	7.91	87

Notes: For each model and each value of the preference parameter λ, this table indicates the optimal inflation forecast horizon (θ) and optimal coefficient values (ρ and α) for rules without an explicit response to the output gap (that is, $\beta \equiv 0$). The table also indicates the percent change in the policy maker's loss function ($\%\Delta\mathcal{L}$) generated by the rule relative to the optimized outcome-based rule.

compassing" is *not* a general characteristic of inflation forecast rules.[29]

V. Robustness of Optimized Rules Under Model Uncertainty

Now we analyze the extent to which optimized forecast-based rules are robust to model uncertainty. We continue to assume that the central bank maintains a permanent commitment to a specific policy rule with parameters that are optimized based on one of the five models. However, we now assume that the true economy is described by a different model; that is, the model used for choosing the policy rule is misspecified.

In the context of forecast-based policies, we need to make a further assumption regarding how expectations are formed in implementing the policy rule. First, we consider the "model consistent" case in which the policy maker's forecasts are based on the true model; that is, the forecasts are unbiased and efficient. Next, we consider the "model inconsistent" case in which the forecasts are constructed from the same misspecified model that has been used for determining the parameters of the policy rule. In the first case, macroeconomic performance suffers because of the suboptimal choice of policy rule parameters; in the second case, systematic forecast errors are added to the problem. While we could consider other variants on model-inconsistent forecasts (such as generating forecasts from a VAR model), we believe that such variants would not substantially change the results reported here.

Our basic method for evaluating robustness is the same for both cases of forecast generation. For a given value of the policy preference parameter λ, we take a given rule X that has been optimized for a specific model—referred to as the "rule-generating" model—and we simulate rule X in a different model—referred to as the "true economy" model. If rule X generates a unique rational expectations equilibrium, then we compute its loss function $\mathcal{L}$ (using the specified value of λ). Now we evaluate the robustness of rule X by comparing its performance with the appropriate outcome-based (OB) policy frontier of the true economy model. Thus, we find the OB policy rule Y that has been optimized for the true economy model subject to the constraint that its interest rate volatility ($\sigma_{\Delta i}$) cannot exceed that implied by rule X. Finally, we compute $\%\Delta\mathcal{L}$, the percent deviation of the loss function value of rule X from that of rule Y, that is, $\%\Delta\mathcal{L}$ measures the relative distance of the loss function of rule X from the relevant OB policy frontier in Figure 5. It should be noted that this measure of robustness involves the unconditional variances of output and inflation, corresponding to our assumption

[29] Our analysis assumes that the output gap is known in real time, whereas in practice the output gap may be subject to persistent measurement errors (cf. Orphanides et al., 2000; McCallum, 2001b). Still, the existence of output gap mismeasurement does not imply that policy should completely exclude a response to the output gap. In a linear-quadratic framework with symmetric information, the optimal response to the efficient output gap estimate is invariant to the degree of mismeasurement (cf., Svensson and Woodford, forthcoming). For simple outcome-based rules, output gap mismeasurement does imply some attenuation—but not complete elimination—of the output gap response (Orphanides, 1998; Frank Smets, 1999; Eric T. Swanson, 2000; Rudebusch, 2001, 2002).

TABLE 5—ROBUSTNESS OF OPTIMIZED RULES WITH MODEL-CONSISTENT FORECASTS

	Optimized for AD-AS				Optimized for FM			
λ	FM	FRB	MSR	TMCM	AD-AS	FRB	MSR	TMCM
0	9	198	1	2	81	7	40	0
⅓	174	33	5	14	831	5	27	12
1	262	40	17	15	ME	9	41	11
3	496	72	33	37	ME	16	57	9

	Optimized for FRB				Optimized for MSR			
λ	AD-AS	FM	MSR	TMCM	AD-AS	FM	FRB	TMCM
0	202	65	16	−2	10	20	5	4
⅓	85	6	2	2	81	27	0	5
1	106	9	5	0	102	29	−4	3
3	120	14	9	−1	118	38	−4	0

	Optimized for TMCM			
λ	AD-AS	FM	FRB	MSR
0	68	15	−3	13
⅓	10	22	17	20
1	ME	42	4	19
3	ME	49	−1	4

Notes: For each value of the preference parameter λ, the optimized rule is taken from the specified "rule-generating" model, and then this rule is evaluated in each alternative "true economy" model using model-consistent forecasts. The notation "ME" indicates that the rule yields multiple equilibria; otherwise, the entry indicates the percent deviation of the loss function from the outcome-based policy frontier of the true economy model ($\%\Delta\mathcal{L}$).

that the central bank maintains a permanent commitment to a specific policy rule. In practice, of course, a central bank can modify its policy strategy if it observes poor stabilization outcomes or acquires other information about the structure of the economy; however, incorporating such a learning process would dramatically increase the complexity and computational intensity of the analysis.

A. *Robustness with Model-Consistent Forecasts*

In this subsection, we assume that the policy rule is optimized using a misspecified model and is implemented using model-consistent forecasts of inflation and output; that is, these forecasts are formulated using the true model of the economy with the actual policy rule in operation. This exercise might be motivated as follows. Suppose that a policy maker develops a forecast-based rule that is optimal in the particular modeling framework that the policy maker prefers to use for this purpose; unfortunately, this model is an imperfect representation of the true economy. The policy maker decides to use the optimized rule to implement monetary policy and communicates this intention to the central bank staff. In implementing the policy rule, the policy maker is willing to use forecasts that are generated using the staff's macroeconometric model; coincidentally, this model happens to be the correct representation of the true economy. In the following section we consider the case in which the central bank staff generates its forecasts using the same (misspecified) model that the policy maker used in choosing the policy rule.[30]

The results of this exercise are reported in the five panels of Table 5, each of which indicates

[30] We do not analyze the performance of rules involving forecasts based on an exogenous or unchanged path for the nominal interest rate; such an approach has been studied by Rudebusch and Svensson (1999). While constant interest rate forecasts can serve to highlight the risks associated with policy inaction, such forecasts ignore relevant information on the central bank's systematic future policy response and are particularly problematic in rational expectations models, in which permanently fixed nominal interest rates generate indeterminacy.

the degree of robustness of rules that have been optimized for the specified model and policy parameter. (Recall that the forecast horizons and coefficients of these rules may be found in Table 3 above.)

In most cases, the optimized rule taken from any particular model is *not* robust across the other four models. For example, taking the rule optimized for the AD-AS model with $\lambda = 1/3$ yields a relative loss of 174 percent in the FM model, while the corresponding rule optimized for FM yields a relative loss of 831 percent in the AD-AS model. Based on these results, a prudent policy maker would be reluctant to rely solely on any rule obtained from the analysis of a single model.

Fortunately, Table 5 does suggest that finding a robust rule is not an impossible task. In particular, the rule optimized for TMCM with $\lambda = 1/3$ yields excellent performance in each of the other models, with relative losses of less than 25 percent. From Table 3, we see that this rule involves a relatively short inflation forecast horizon ($\theta = 2$), as well as a substantial interest rate smoothing (ρ near unity) and a nontrivial response to the current output gap.

In contrast, although not shown here, forecast-based rules with no explicit output gap response (that is, $\beta \equiv 0$) are subject to potentially disastrous performance in the face of model uncertainty, especially when the policy maker places nontrivial weight on output stability.[31] As we saw in Table 4, these rules not only omit an explicit output gap response but also typically involve a low degree of interest rate smoothing and a highly aggressive response to a relatively long-horizon inflation forecast. And as noted above, rules with these characteristics are prone to yielding indeterminacy and are typically not very robust to model uncertainty.

B. *Robustness with Model-Inconsistent Forecasts*

Now we investigate the consequences of using model-inconsistent forecasts; that is, we assume that the policy rule is optimized using a misspecified model and that the rule is then implemented using forecasts generated by the same misspecified model. After determining the optimized policy rule for a particular model, we obtain the reduced-form representations of the relevant inflation and output gap forecasts in terms of the state variables of the model, and we add these reduced-form forecast equations to the model of the true economy. The policy rule is expressed in terms of the misspecified forecasts, which are obtained by evaluating these reduced-form forecast equations using the data generated by the true economy model. Thus, this procedure presumes that the state variables from the policy maker's model also appear in the true economy model; that is, the misspecified model is nested within the true economy model. For this reason, we consider cases in which the FM model constitutes the policy maker's model while one of the other three models represents the true economy, and we also consider cases in which the MSR model constitutes the policy maker's model while either FRB or TMCM represents the true economy.

The results of this exercise are reported in the upper part of Table 6. As in the preceding subsection, we evaluate the relative performance ($\%\Delta\mathcal{L}$) of each policy rule compared with the optimized outcome-based rule that generates the same level of interest rate volatility in the true economy model. Comparing these results regarding the robustness of forecast-based rules with the outcomes presented in Table 5 (repeated in the lower part of Table 6), we find that in most cases performance deteriorates when the model-inconsistent forecast is used, especially in the case of rules optimized in the MSR model and evaluated in the FRB or TMCM models. However, there are exceptions to this pattern, for example in the case of rules optimized in the FM model and evaluated in the MSR model. Overall, the magnitude of the difference in loss compared to the optimized OB rule is not very large and never exceeds 50 percent.

C. *Rules with Fixed Forecast Horizons*

We have seen that optimized rules involve relatively short forecast horizons (0–4 quarters) and can be very robust to model uncertainty. Now we consider the degree of robustness of rules with longer forecast horizons. In particular, we analyze the performance of rules in which the inflation forecast horizon is fixed at either one or two years (that is, $\theta = 4$ or 8), and

[31] These results are reported in Levin et al. (2001).

TABLE 6—IMPLICATIONS OF MODEL-INCONSISTENT FORECASTS

	λ	Optimized for FM			Optimized for MSR	
		FRB	MSR	TMCM	FRB	TMCM
Model-inconsistent forecasts	0	14	39	5	4	—
	⅓	6	14	9	3	14
	1	14	19	15	11	32
	3	25	25	22	21	45
Model-consistent forecasts	0	7	40	−0	5	4
	⅓	5	27	12	−0	5
	1	9	41	11	−4	3
	3	6	57	9	−4	0

Notes: For each value of the preference parameter λ, the optimized rule is taken from the specified "rule-generating" model (either FM or MSR), and then this rule is evaluated in each alternative "true economy" model. In the upper panel, the rule is implemented using forecasts obtained from the rule-generating model; in the lower panel, the rule is implemented using forecasts obtained from the true economy model (as in Table 5). Each entry indicates the percent deviation of the loss function from the outcome-based policy frontier of the true economy model (%$\Delta\mathcal{L}$).

TABLE 7—COEFFICIENTS OF OPTIMIZED RULES WITH FIXED FORECAST HORIZONS

		$\theta = 4, \kappa = 0$			$\theta = 8, \kappa = 0$			$\theta = 4, \kappa = 4$		
Model	λ	ρ	α	β	ρ	α	β	ρ	α	β
FM	0	0.88	0.65	−0.00	1.19	2.05	−0.04	1.03	0.78	0.11
	⅓	0.94	0.54	0.32	1.07	0.58	0.46	1.00	0.85	0.49
	1	0.85	0.39	0.50	0.84	0.61	0.50	1.02	0.73	0.90
	3	0.82	0.21	0.64	0.82	0.32	0.60	1.04	0.48	1.13
FRB	0	1.27	5.31	0.04	2.50	49.22	−0.05	1.28	5.53	0.02
	⅓	1.01	1.01	1.00	0.99	1.13	0.96	2.12	8.65	6.79
	1	1.03	0.54	1.10	1.03	0.61	1.08	2.22	5.97	8.84
	3	1.03	0.30	1.13	1.03	0.33	1.12	2.11	3.38	8.69
MSR	0	0.95	8.39	−0.33	0.97	18.96	0.65	1.00	4.16	−0.35
	⅓	1.11	2.21	1.38	1.12	3.85	1.44	1.80	28.00	24.00
	1	1.08	1.20	1.42	1.09	1.81	1.47	1.80	16.00	24.00
	3	1.05	0.65	1.41	1.06	0.89	1.44	1.80	8.00	24.00
TMCM	0	1.74	14.77	0.30	1.27	12.90	2.17	1.82	17.11	0.26
	⅓	1.02	1.92	1.39	1.04	6.22	1.73	1.06	13.53	10.21
	1	0.97	0.80	1.47	0.96	0.04	1.53	1.00	7.87	9.74
	3	0.95	0.42	1.49	0.95	0.04	1.53	1.23	6.12	12.00

that respond either to the current output gap or to its one-year-ahead forecast (that is, $\kappa = 0$ or 4). For a given value of λ and a given combination of the output and inflation forecast horizons, we determine the optimal coefficients (ρ, α, and β) for each model, and then proceed to evaluate its performance in each of the other models, following the methodology described above.

For brevity, we focus on the robustness of rules obtained from each of the four macroeconometric models and implemented in the optimizing AD-AS model using model-consistent forecasts; additional robustness results may be found in Levin et al. (2001). The coefficients of the optimized rules are reported in Table 7, while Table 8 indicates the relative loss of each rule (%$\Delta\mathcal{L}$) compared with the OB policy frontier of the AD-AS model.[32]

[32] In the MSR and TMCM models, the optimized rules obtained for $\theta = \kappa = 4$ lie right on the edge of the

TABLE 8—ROBUSTNESS OF FIXED-HORIZON RULES IN THE OPTIMIZING AD-AS MODEL

Forecast horizons			Rule-generating model			
θ	κ	λ	FM	FRB	MSR	TMCM
4	0	0	210	191	ME	216
		⅓	26	13	10	12
		1	34	10	8	13
		3	38	11	10	16
8	0	0	ME	ME	ME	ME
		⅓	10	12	9	ME
		1	31	9	7	11
		3	25	11	9	14
4	4	0	194	204	ME	221
		⅓	ME	ME	ME	ME
		1	ME	ME	ME	ME
		3	ME	ME	ME	ME

Notes: For each value of the preference parameter λ and each choice of the inflation forecast horizon θ and output gap forecast horizon κ, the coefficients of the rule are optimized using the specified "rule-generating" model (as shown in the previous table), and then this rule is evaluated in the optimizing AD-AS model using model-consistent forecasts. Each entry indicates the percent deviation of the loss function from the outcome-based policy frontier of the optimizing AD-AS model (%$\Delta\mathcal{L}$); the notation "ME" indicates that the rule yields multiple equilibria.

Forecast-based rules that respond to a four-quarter inflation forecast and the current output gap are generally quite robust to model uncertainty, especially when the policy maker places nonnegligible weight on stabilizing output as well as inflation ($\lambda > 0$). In contrast, optimized rules with an eight-quarter inflation forecast horizon or a four-quarter output gap forecast are markedly less robust, including a much greater incidence of multiple equilibria. This lack of robustness primarily reflects the substantial differences in output and inflation dynamics across the various models.

VI. Identifying a Robust Benchmark Rule

Our previous analysis has highlighted the general characteristics of forecast-based rules that are robust to model uncertainty; in this section, we proceed to identify a specific rule that can serve as a robust benchmark for monetary policy. None of the rules taken from the literature (listed in Table 1) is satisfactory for this purpose: most of those rules generate indeterminacy in one or more of the five models (see Table 2), while the remaining rules perform quite poorly relative to the outcome-based policy frontier.[33] Therefore, for each value of the preference parameter λ, we now determine the policy rule that minimizes the average loss function across all five models, subject to an upper bound on the level of interest rate volatility in each model.

In particular, we assume that the policy maker's loss function $\bar{\mathcal{L}}$ is given by:

$$(6)\quad \bar{\mathcal{L}} = \tfrac{1}{5}\left(\mathcal{L}_{OPT} + \mathcal{L}_{FM} + \mathcal{L}_{FRB} + \mathcal{L}_{MSR} + \mathcal{L}_{TMCM}\right),$$

where $\mathcal{L}_x$ is the value of the loss function (5) obtained by evaluating a particular policy rule in model x. Thus, from a Bayesian perspective, $\bar{\mathcal{L}}$ corresponds to the *expected* loss function when the policy maker has flat prior beliefs regarding which of these five models is the correct representation of the economy.

In light of our earlier results, we focus exclusively on the class of rules that respond to the one-year-ahead forecast of the smoothed inflation rate and to the current output gap (that is, rules with $\theta = 4$ and $\kappa = 0$). Thus, for a given value of λ, we find the values of the policy parameters (α, β, and ρ) that minimize $\bar{\mathcal{L}}$, subject to the constraint that in every model the unconditional standard deviation of Δi_t cannot exceed the value generated by the estimated benchmark rule. The results of this optimization are reported in Table 9.

For a policy maker who is concerned solely with stabilizing inflation ($\lambda = 0$), the optimized rule works very well in several of the macroeconometric models but performs poorly in the optimizing AD-AS model. In this case, it is apparent that *no* four-quarter-ahead inflation forecast-based rule provides near-optimal

indeterminacy region. For the set of rules that yield a unique stationary equilibrium, the optimum is obtained by rules that generate less interest rate variability than the estimated benchmark rule; this is the only case in our analysis for which the interest rate variability constraint is not binding.

[33] The performance of these rules is reported in Levin et al. (2001).

TABLE 9—MINIMIZING THE AVERAGE LOSS ACROSS ALL FIVE MODELS

	Optimal parameters			Stabilization performance (%$\Delta\mathcal{L}$)				
λ	ρ	α	β	Optimizing AD-AS	FM	FRB	MSR	TMCM
0	1.02	0.66	0.08	139	1	0	42	1
⅓	0.97	0.45	0.41	19	9	9	15	1
1	0.92	0.30	0.53	23	7	14	15	1
3	0.89	0.19	0.60	29	4	22	18	4

Notes: For each value of the preference parameter λ, the corresponding row of this table indicates the parameters and stabilization performance of the optimized rule (with fixed forecast horizons $\theta = 4$ and $\kappa = 0$) that minimizes the average loss function $\bar{\mathcal{L}}$ across all five models, subject to the constraint that in every model the unconditional standard deviation of Δi_t cannot exceed the value generated by the estimated benchmark rule. The stabilization performance in each model is measured by the period deviation of the loss function from the OB policy frontier of that model (%$\Delta\mathcal{L}$).

performance in every model.[34] Thus, the rule given in Table 9 is the optimal choice for a policy maker with flat priors concerning the relative accuracy of the five models; this rule would also be near optimal for any policy maker who has reasonable confidence in the four macroeconometric models and is relatively skeptical about the accuracy of the optimizing AD-AS model. In contrast, this rule would be far from optimal for a policy maker who discounts the relevance of the four macroeconometric models and who has strong prior beliefs that the optimizing AD-AS model is the best representation of the true economy.

For a policy maker who is concerned with stabilizing both inflation and the output gap ($\lambda > 0$), we find that each optimized rule performs remarkably well in all five models, especially considering the dramatically different dynamic properties of these models. For example, when $\lambda = 1/3$, Table 9 indicates that the loss function value generated by the optimized rule never deviates more than 20 percent from the outcome-based policy frontier of each model. Evidently, choosing the policy parameters to minimize the average loss function across the five models does not generate large stabilization costs relative to fine-tuning these parameters to a given model. Thus, the same rule would be nearly optimal even for a policy maker with very different (nonflat) prior beliefs about the accuracy of the five models.

It is also striking that the policy rule parameters in Table 9 are quite similar for all three nonzero values of λ. This suggests the possibility of identifying a benchmark rule that performs well for a fairly wide range of policy preferences as well as for a wide range of prior beliefs about the dynamic properties of the economy.

Therefore, we now consider the following simple forecast-based policy rule, which has parameter values nearly identical to those of the optimized rule for $\lambda = 1/3$:

$$(7) \quad i_t = 1.0 i_{t-1} + 0.4 E_t(\tilde{\pi}_{t+4} - \pi^*) + 0.4 y_t.$$

Table 10 indicates the stabilization performance of this rule for each value of the preference parameter λ. As one would expect, the rule performs very well in all five models when $\lambda = 1/3$. This rule also performs remarkably well when $\lambda = 1$; as in the previous case, the loss function never deviates more than 20 percent from the outcome-based policy frontier. The rule provides reasonably robust performance even for $\lambda = 3$, although the maximum value of %$\Delta\mathcal{L}$ does reach nearly 50 percent in this case. Based on these results, we conclude that this rule can serve as a robust benchmark for monetary policy, at least for policy makers who place nontrivial weight on stabilizing the output gap as well as the inflation rate.[35]

[34] In contrast, an outcome-based rule can be obtained that performs very well for $\lambda = 0$ in all five models.

[35] It should be noted that one can also obtain an outcome-based rule that yields robust performance for $\lambda \geq 1/3$ in all five models.

TABLE 10—STABILIZATION PERFORMANCE OF THE BENCHMARK FORECAST-BASED RULE

λ	Optimizing AD-AS	FM	FRB	MSR	TMCM
0	278	76	57	379	13
⅓	16	12	7	16	1
1	19	7	20	6	0
3	22	23	48	12	0

Note: For each value of the preference parameter λ, the corresponding row of this table indicates the percent deviation of the loss function obtained by the benchmark forecast-based rule [given in equation (7)] from the OB policy frontier of each model (%$\Delta\mathcal{L}$).

VII. Conclusion

In this paper, we have analyzed the performance and robustness of forecast-based monetary policy rules using five models that reflect divergent views about the dynamic properties of the U.S. economy. Our analysis yields the following conclusions:

- While forecast-based rules can serve as a useful framework for monetary policy, this class of rules does not provide substantial gains in stabilization performance compared with simple outcome-based rules.
- Robust policy rules respond to a short-horizon forecast (not exceeding one year) of a smoothed measure of inflation, incorporate an explicit response to the current output gap, and involve a relatively high degree of policy inertia.
- We have identified a specific forecast-based rule that can serve as a robust benchmark for monetary policy; this rule performs remarkably well in all five models for a wide range of policy preferences.

Our analysis also suggests several fruitful areas for future research. First, while this paper has focused exclusively on models with rational expectations and short-run nominal inertia, our methodology can be applied to an even broader set of models that incorporate alternative assumptions about expectations formation and about the transmission mechanism of monetary policy. Second, our analysis has focused exclusively on models of the U.S. economy; in future work, it will be interesting to follow a similar approach in identifying robust policy rules for other economies with different structural characteristics (e.g., small open economies and emerging market economies). Third, we have proceeded under the assumption that the parameters of each competing model are known exactly and that the data series are measured precisely; for example, we have assumed that the output gap is known in real time, whereas in practice the output gap may be subject to persistent measurement errors. Thus, additional research will be required to identify rules that are robust to data uncertainty and to parameter uncertainty as well as to model uncertainty. Finally, our analysis has assumed that the central bank maintains a permanent commitment to a particular monetary policy rule; in future research, it will be interesting to consider the problem of designing robust policies for an environment in which the central bank can make ongoing policy adjustments as it accumulates additional information about the underlying structure of the economy.

REFERENCES

Amano, Robert; Coletti, Don and Macklem, Tiff. "Monetary Rules When Economic Behaviour Changes." Bank of Canada Working Paper No. 99–8, April 1999.

Amato, Jeffery D. and Laubach, Thomas. "Implications of Habit Formation for Optimal Monetary Policy." Board of Governors of the Federal Reserve System Finance and Economics Discussion Series Working Paper No. 2001–58, December 2001.

Anderson, Gary and Moore, George. "A Linear Algebraic Procedure for Solving Linear Perfect Foresight Models." *Economics Letters*, 1985, *17*(3), pp. 247–52.

Balvers, Ronald and Cosimano, Thomas. "Inflation Variability and Gradualist Monetary Policy." *Review of Economic Studies*, October 1994, *61*(4), pp. 721–38.

Batini, Nicoletta and Haldane, Andrew. "Forward-Looking Rules for Monetary Policy," in John B. Taylor, ed., *Monetary policy rules*. Chicago: University of Chicago Press, 1999, pp. 157–92.

Batini, Nicoletta and Nelson, Edward. "Optimal Horizons for Inflation Targeting." *Journal of Economic Dynamics and Control*, June 2001, *25*(6–7), pp. 891–910.

Becker, Robin G.; Dwolatsky, Barry; Karakitsos, Elias and Rustem, Berc. "The Simultaneous Use of Rival Models in Policy Optimisation." *Economic Journal*, June 1986, *96*(382), pp. 425–48.

Bernanke, Ben S.; Laubach, Thomas; Mishkin, Frederic S. and Posen, Adam. *Inflation targeting: Lessons from the international experience*. Princeton, NJ: Princeton University Press, 1999.

Bernanke, Ben S. and Mishkin, Frederic S. "Inflation Targeting: A New Framework for Monetary Policy?" *Journal of Economic Perspectives*, Winter 1997, *11*(2), pp. 97–116.

Bernanke, Ben S. and Woodford, Michael. "Inflation Forecasts and Monetary Policy." *Journal of Money, Credit, and Banking*, November 1997, Pt. 2, *29*(4), pp. 65–84.

Black, Richard; Cassino, Vincenzo; Drew, Aaron; Hansen, Eric; Hunt, Benjamin; Rose, David and Scott, Alasdair. "The Forecasting and Policy System: The Core Model." Reserve Bank of New Zealand Research Paper No. 43, August 1997a.

Black, Richard; Macklem, Tiff and Rose, David. "On Policy Rules for Price Stability," in Tiff Macklem, ed., *Price stability, inflation targets and monetary policy*. Ottawa: Bank of Canada, 1997b, pp. 411–61.

Blanchard, Olivier J. and Kahn, Charles M. "The Solution of Linear Difference Models under Rational Expectations." *Econometrica*, July 1980, *48*(5), pp. 1305–13.

Brainard, William. "Uncertainty and the Effectiveness of Policy." *American Economic Review*, May 1967 (*Papers and Proceedings*), *57*(2), pp. 411–25.

Brayton, Flint; Levin, Andrew; Tryon, Ralph and Williams, John C. "The Evolution of Macro Models at the Federal Reserve Board." *Carnegie-Rochester Conference Series on Public Policy*, December 1997, *47*, pp. 43–81.

Chinn, Menzie and Dooley, Michael. "Monetary Policy in Japan, Germany and the United States: Does One Size Fit All?" National Bureau of Economic Research (Cambridge, MA) Working Paper No. 6092, July 1997.

Christiano, Lawrence J.; Eichenbaum, Martin and Evans, Charles L. "The Effects of Monetary Policy Shocks: Evidence from the Flow of Funds." *Review of Economics and Statistics*, February 1996, *78*(1), pp. 16–34.

Christiano, Lawrence J. and Gust, Christopher. "Comment on 'Robustness of Simple Policy Rules under Model Uncertainty'," in John B. Taylor, ed., *Monetary policy rules*. Chicago: University of Chicago Press, 1999, pp. 299–316.

Christodoulakis, Nico; Kemball-Cook, David and Levine, Paul. "The Design of Economic Policy under Model Uncertainty." *Computational Economics*, November 1993, *6*(3–4), pp. 219–40.

Clarida, Richard; Gali, Jordi and Gertler, Mark. "Monetary Policy Rules in Practice: Some International Evidence." *European Economic Review*, June 1998, *42*(6), pp. 1003–67.

______. "The Science of Monetary Policy: A New Keynesian Perspective." *Journal of Economic Literature*, December 1999, *37*(4), pp. 1661–707.

______. "Monetary Policy Rules and Macroeconomic Stability: Evidence and Some Theory." *Quarterly Journal of Economics*, February 2000, *115*(1), pp. 147–80.

Clarida, Richard and Gertler, Mark. "How the Bundesbank Conducts Monetary Policy," in Christina Romer and David Romer, eds., *Reducing inflation: Motivation and strategy*. Chicago: University of Chicago Press, 1997, pp. 363–406.

de Brouwer, Gordon and Ellis, Luci. "Forward-looking Behaviour and Credibility: Some Evidence and Implications for Policy." Reserve Bank of Australia Research Discussion Paper No. 9803, February 1998.

Dennis, Richard and Söderström, Ulf. "How Important Is Precommitment for Monetary Policy?" Federal Reserve Bank of San Francisco Working Paper No. 02–10, September 2002.

Erceg, Christopher J.; Henderson, Dale W. and Levin, Andrew T. "Optimal Monetary Policy with Staggered Wage and Price Contracts." *Journal of Monetary Economics*, October 2000, *46*(2), pp. 281–313.

Erceg, Christopher J. and Levin, Andrew T. "Optimal Monetary Policy with Durable and Non-Durable Goods." Mimeo, Board of Governors of the Federal Reserve System, December 2001.

Frankel, Jeffrey A. and Rockett, Katherine. "International Macroeconomic Policy Coordination when Policymakers Do Not Agree on the True Model." *American Economic Review*, June 1988, *78*(3), pp. 318–40.

Fuhrer, Jeffrey C. "Habit Formation in Consumption and Its Implications for Monetary-Policy Models." *American Economic Review*, June 2000, *90*(3), pp. 367–90.

Fuhrer, Jeffrey C. and Madigan, Brian. "Monetary Policy When Interest Rates Are Bounded at Zero." *Review of Economics and Statistics*, November 1997, *79*(4), pp. 573–85.

Fuhrer, Jeffrey C. and Moore, George. "Inflation Persistence." *Quarterly Journal of Economics*, February 1995, *110*(1), pp. 127–59.

Giannoni, Marc P. "Optimal Interest-Rate Rules in a Forward-Looking Model, and Inflation Stabilization versus Price-Level Stabilization." Mimeo, Federal Reserve Bank of New York, September 2000.

Goodfriend, Marvin. "Interest Rate and the Conduct of Monetary Policy." *Carnegie-Rochester Conference Series on Public Policy*, Spring 1991, *34*, pp. 7–30.

Goodhart, Charles A. E. "Can Central Banking Survive the IT Revolution?" *International Finance*, July 2000, *3*(2), pp. 189–209.

Haldane, Andrew, ed. *Targeting inflation*. London: Bank of England, 1995.

Hansen, Lars P. and Sargent, Thomas J. "Robust Control and Economic Model Uncertainty." *American Economic Review*, May 2001 (*Papers and Proceedings*), *91*(2), pp. 60–66.

Holtham, Gerald and Hughes-Hallett, Andrew. "International Macroeconomic Policy Coordination When Policymakers Do Not Agree on the True Model: Comment." *American Economic Review*, September 1992, *82*(4), pp. 1043–51.

Isard, Peter; Laxton, Douglas and Eliasson, Ann-Charlotte. "Simple Monetary Policy Rules under Model Uncertainty." International Monetary Fund Working Paper No. 99/75, May 1999.

Jansson, Per and Vredin, Anders. "Forecast-based Monetary Policy in Sweden 1992–1998: A View from Within." Sveriges Riksbank Working Paper No. 120, February 2001.

Karakitsos, Elias and Rustem, Berc. "Optimally Derived Fixed Rules and Indicators." *Journal of Economic Dynamics and Control*, October 1984, *8*(1), pp. 33–64.

Kendrick, David. "Caution and Probing in a Macroeconomic Model." *Journal of Economic Dynamics and Control*, May 1982, *4*(2), pp. 149–70.

Kerr, William and King, Robert G. "Limits on Interest Rate Rules in an IS Model." *Federal Reserve Bank of Richmond Economic Quarterly*, Spring 1996, *82*(2), pp. 47–75.

King, Mervyn. "Changes in UK Monetary Policy: Rules and Discretion in Practice." *Journal of Monetary Economics*, June 1997, *39*(1), pp. 81–97.

Laxton, Douglas; Rose, David and Tetlow, Robert. "Monetary Policy, Uncertainty and the Presumption of Linearity." Mimeo, Bank of Canada, August 1993.

Leiderman, Leonardo and Svensson, Lars E. O., eds. *Inflation targets*. London: Centre for Economic Policy Research, 1995.

Levin, Andrew T.; Wieland, Volker and Williams, John C. "Robustness of Simple Monetary Policy Rules under Model Uncertainty," in John B. Taylor, ed., *Monetary policy rules*. Chicago: University of Chicago Press, 1999, pp. 263–99.

______ **.** "The Performance of Forecast-Based Monetary Policy Rules under Model Uncertainty." European Central Bank Working Paper No. 68, July 2001.

McCallum, Bennett T. "Robustness Properties of a Rule for Monetary Policy." *Carnegie-Rochester Conference Series on Public Policy*, Autumn 1988, *29*, pp. 173–203.

______ **.** "Role of the Minimal State Variable Criterion in Rational Expectations Models." *International Tax and Public Finance*, November 1999, *6*(4), pp. 621–39.

______ **.** "Monetary Policy Analysis in Models without Money." *Federal Reserve Bank of St. Louis Review*, July–August 2001a, *83*(4), pp. 145–60.

______ **.** "Should Monetary Policy Respond Strongly to Output Gaps?" *American Economic Review*, May 2001b (*Papers and Proceedings*), *91*(2), pp. 258–62.

Onatski, Alexei and Stock, James H. "Robust Monetary Policy under Model Uncertainty in a Small Model of the U.S. Economy." *Macroeconomic Dynamics*, February 2002, *6*(1), pp. 85–110.

Orphanides, Athanasios. "Monetary Policy Evaluation with Noisy Information." Board of Governors of the Federal Reserve System Finance and Economics Discussion Series Working Paper No. 1998–50, November 1998.

______ **.** "Monetary Policy Rules Based on Real-Time Data." *American Economic Review*, September 2001, *91*(4), pp. 964–85.

Orphanides, Athanasios; Porter, Richard D.; Reifschneider, David; Tetlow, Robert and Finan, Frederico. “Errors in the Measurement of the Output Gap and the Design of Monetary Policy.” *Journal of Economics and Business*, January–April 2000, *52*(1–2), pp. 117–41.

Orphanides, Athanasios and Wieland, Volker. “Price Stability and Monetary Policy Effectiveness when Nominal Interest Rates are Bounded at Zero.” Board of Governors of the Federal Reserve System Finance and Economics Discussion Series Working Paper No. 1998–35, August 1998.

______ **.** “Inflation Zone Targeting.” *European Economic Review*, June 2000a, *44*(7), pp. 1351–87.

______ **.** “Efficient Monetary Policy Design Near Price Stability.” *Journal of the Japanese and International Economies*, December 2000b, *14*(4), pp. 327–65.

Reifschneider, David; Tetlow, Robert and Williams, John. “Aggregate Disturbances, Monetary Policy, and the Macroeconomy: The FRB/US Perspective.” Federal Reserve Bulletin, January 1999, *85*(1), pp. 1–19.

Reifschneider, David and Williams, John C. “Three Lessons for Monetary Policy in a Low Inflation Era.” *Journal of Money, Credit, and Banking*, November 2000, *32*(4), pp. 936–66.

Rotemberg, Julio J. and Woodford, Michael. “Interest-Rate Rules in an Estimated Sticky Price Model,” in John B. Taylor, ed., *Monetary policy rules*. Chicago: University of Chicago Press, 1999, pp. 57–119.

Rudebusch, Glenn D. “Is the Fed Too Timid? Monetary Policy in an Uncertain World.” *Review of Economics and Statistics*, May 2001, *83*(2), pp. 203–17.

______ **.** “Assessing Nominal Income Rules for Monetary Policy with Model and Data Uncertainty.” *Economic Journal*, April 2002, *112*(479), pp. 402–32.

Rudebusch, Glenn D. and Svensson, Lars E. O. “Policy Rules for Inflation Targeting,” in John B. Taylor, ed., *Monetary policy rules*. Chicago: University of Chicago Press, 1999, pp. 203–53.

Sack, Brian and Wieland, Volker. “Interest Rate Smoothing and Optimal Monetary Policy: A Review of Recent Empirical Evidence.” *Journal of Economics and Business*, January–April 2000, *52*(1–2), pp. 205–28.

Schaechter, Andrea; Stone, Mark R. and Zelmer, Mark. “Adopting Inflation Targeting: Practical Issues for Emerging Market Countries.” International Monetary Fund Occasional Paper No. 202, December 2000.

Smets, Frank. “Output Gap Uncertainty: Does It Matter for the Taylor Rule?” in Benjamin Hunt and Adrian Orr, eds., *Monetary policy under uncertainty*. Wellington, New Zealand: Reserve Bank of New Zealand, 1999, pp. 10–29.

Söderlind, Paul. “Solution and Estimation of RE Macromodels with Optimal Policy.” *European Economic Review*, April 1999, *43*(4–6), pp. 813–23.

Svensson, Lars E. O. “Inflation Forecast Targeting: Implementing and Monitoring Inflation Targets.” *European Economic Review*, June 1997, *41*(6), pp. 1111–46.

______ **.** “Inflation Targeting as a Monetary Policy Rule.” *Journal of Monetary Economics*, June 1999, *43*(3), pp. 607–54.

______ **.** “Requiem for Forecast-Based Instrument Rules.” Mimeo, Princeton University, March 2001.

Svensson, Lars E. O. and Woodford, Michael. “Implementing Optimal Policy through Inflation-Forecast Targeting.” Mimeo, Princeton University, November 1999.

______ **.** “Indicator Variables for Optimal Policy.” *Journal of Monetary Economics* (forthcoming).

Swanson, Eric T. “On Signal Extraction and Non-Certainty-Equivalence in Optimal Monetary Policy Rules.” Board of Governors of the Federal Reserve System Finance and Economics Discussion Series Working Paper No. 2000–32, June 2000.

Taylor, John B. “Estimation and Control of a Macroeconomic Model with Rational Expectations.” *Econometrica*, September 1979, *47*(5), pp. 1267–86.

______ **.** *Macroeconomic policy in a world economy*. New York: Norton, 1993.

______ **.** “The Robustness and Efficiency of Monetary Policy Rules as Guidelines for Interest Rate Setting by the European Central Bank.” *Journal of Monetary Economics*, June 1999a, *43*(3), pp. 655–79.

______ **.** “Introduction,” in John B. Taylor, ed., *Monetary policy rules*. Chicago: University of Chicago Press, 1999b, pp. 1–14.

______ **.** ed., *Monetary policy rules*. Chicago: University of Chicago Press, 1999c.

Tetlow, Robert. "Inflation Targeting and Target Instability." Board of Governors of the Federal Reserve System Finance and Economics Discussion Series Working Paper No. 2000–1, January 2000.

Tetlow, Robert and von zur Muehlen, Peter. "Robust Monetary Policy with Misspecified Models: Does Model Uncertainty Always Call for Attenuated Policy?" *Journal of Economic Dynamics and Control*, June 2001, *25*(6–7), pp. 911–49.

von zur Muehlen, Peter. "Activist vs. Non-Activist Monetary Policy: Optimal Rules under Extreme Uncertainty." Mimeo, Board of Governors of the Federal Reserve System, 1982.

Wieland, Volker. "Monetary Policy, Parameter Uncertainty and Optimal Learning." *Journal of Monetary Economics*, August 2000, *46*(1), pp. 199–228.

Williams, John C. "Simple Rules for Monetary Policy." Board of Governors of the Federal Reserve System Finance and Economics Discussion Series Working Paper No. 1999–12, February 1999.

Wolman, Alexander L. "Real Implications of the Zero Bound on Nominal Interest Rates." Mimeo, Federal Reserve Bank of Richmond, November 1998.

Woodford, Michael. "Optimal Monetary Policy Inertia." *Manchester School*, Supplement 1999, *67*, pp. 1–35.

______ . "Pitfalls of Forward-Looking Monetary Policy." *American Economic Review*, May 2000 (*Papers and Proceedings*), *90*(2), pp. 100–04.

______ . *Interest and prices: Foundations of a theory of monetary policy*. Princeton, NJ: Princeton University Press (forthcoming).