Simple Rules for Monetary Policy

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Abstract

What is a good monetary policy rule for stabilizing the economy? In this paper, efficient policy rules are computed using the FRB/US large-scale open-economy macroeconometric model. Simple three-parameter policy rules are found to be very effective at minimizing fluctuations in inflation, output, and interest rates: Increases in rule complexity yield only trivial reductions in aggregate variability. Under rational expectations, efficient policies smooth the interest rate response to shocks and use the feedback from anticipated policy actions to stabilize inflation and output and to moderate movements in short-term interest rates. Policy should react to a multi-period inflation rate rather than the current quarter inflation rate; in fact, targeting the price level, as opposed to the inflation rate, involves only small additional stabilization costs. These results are robust to parameter and model uncertainty and the imposition of the non-negativity constraint on nominal interest rates. However, if expectations formation is invariant to policy, as in backward-looking models, the expectations channel is shut off and the performance of policies that are efficient under rational expectations may, as a result, deteriorate markedly; efficient policies, in contrast, exploit systematic expectational errors.

Keywords: monetary policy rules, macroeconometric models, rational expectations

JEL Classification E52, F41

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What is a good monetary policy rule for stabilizing the economy? Confidence in model-based answers to this question has waxed and waned over the last three decades. By the 1970s, application of optimal control techniques to estimated macro models appeared to provide a precise answer based on a concrete description of policy makers' preferences and the law of motion of the economy. This approach then came under attack from two sides. Lucas (1976) decried the fact that the structural parameters of the macroeconomic models used for policy evaluation were assumed to be invariant to policy, contradicting the notion of optimizing agents. Moreover, Kydland and Prescott (1977) argued that such policies were in any case time inconsistent, that is, a policy maker would find it advantageous to deviate from the "optimal" policy rule. In this paper, we evaluate monetary policy rules using the FRB/US large-scale open-economy macroeconometric model, which, in response to the Lucas' Critique, features explicit intertemporal optimization-based microfoundations and rational expectations. We focus on simple rules, the transparency of which may increase the visibility of discretionary policy actions and thereby reduce their effectiveness, lessening policymakers' incentive to deviate from the rule.

The approach to evaluating monetary policy rules used in this paper follows the tradition dating to Phillips (1954), in which a macroeconomic model is used to compute the policy that minimizes a measure of fluctuations in prices, resource utilization, and interest rates. Because we are interested in the "average" or "long-run" performance of polices, we compute the unconditional moments that correspond to the outcomes from an infinitely long stochastic simulation of the model.[1] For backward-looking models, the computational burden of this analysis is generally not especially great. However, for forward-looking models with rational (model-consistent) expectations, the computational cost can be orders of magnitude greater. The constraint on computer resources has forced past work in two directions. Policy evaluation using large-scale rational expectations models has been limited to comparisons of small sets of policies, as in Bryant, Currie, Frenkel, Masson and Portes (1989), Bryant, Hooper and Mann (1993), and Taylor (1993b). The alternative approach has been to use small-scale rational expectations models, as in Fischer (1977), Phelps and Taylor (1977), Taylor (1979), Fuhrer (1997a), Tetlow

[1] An alternative approach is to conduct a single model simulation using the historical time series of residuals as disturbances (McCallum (1988) and Fair and Howrey (1996)). This method has the advantage that simulated outcomes can be compared directly to the historical outcomes, but suffers from the disadvantage that results depend on the particular historical draw of disturbances and thus may not in general provide an accurate indication of the relative performance of policies.

and von zur Muehlen (1996), and Svensson (1999a), for which the computation cost of computing moments is relatively low.

In addition to being easy to solve, small-scale models have the advantage of being relatively transparent. System properties are a function of a small set of parameters that often favor straightforward interpretation, such as the slope of the IS curve or the response of inflation to unemployment. Properties of large-scale models, on the other hand, depend on a large number of parameter values, sectoral linkages, and shocks, which complicates the interpretation of results. Nonetheless, for policy evaluation, there are distinct advantages to models such as FRB/US that provide a rich description of the economic environment facing policymakers.

One advantage of using the FRB/US model is that it differentiates between a wide range of disturbances to the economy and their idiosyncratic effects across sectors. For example, productivity, imported oil prices, and wages are each modeled separately and their effects on prices and real activity differ in significant ways. In contrast, in small-scale models, disturbances to these variables are subsumed into the residuals of the price or potential output equations (Ball and Mankiw 1995). An important feature of the disaggregated nature of FRB/US is that it includes estimated equations for various categories of trade, import prices, foreign variables, and the exchange value of the dollar. The exchange rate channel contributes a significant potion of the total effect of monetary policy on prices and output (Reifschneider, Tetlow and Williams 1999); this channel is subsumed into the IS curve in small-scale models. Furthermore, the model accounts for changes in capital stocks and the value of wealth. In this way, the intertemporal linkages related to investment in physical capital and wealth accumulation are better described than in small-scale structural models constructed on a strictly flow basis.

Recent increases in computer speed and the development of more efficient model solution algorithms now make the detailed evaluation of monetary policies in large-scale rational expectations models such as FRB/US feasible. The results of such an analysis are in many ways surprising. We find that parsimonious specifications of rules where the funds rate is determined by the lagged funds rate, a multi-period inflation rate, and the current output gap are very effective at reducing variability in inflation, output, and the short-term interest rate. Although the policy maker faces a "complex world" in the FRB/US model, increasing the number of variables in the policy rule beyond these three yields only trivial reductions in aggregate variability.

A key characteristic of successful policies under rational expectations is a strong degree of persistence in movements in the federal funds rate. Efficient policies smooth the interest rate response to shocks and use the feedback from the anticipation that movements of the federal funds rate will be sustained to stabilize inflation and output, with only moderate movements in short-term interest rates. Specifically, a small but sustained rise in the funds rate achieves the same change in the current bond rate as a large short-lived increase in the funds rate, but with far less variability in short-term interest rates (Goodfriend 1991). Interestingly, targeting the price level rather than the inflation rate generates little additional cost in terms of output and inflation variability. Under price level targeting, the expectations channel helps stabilize inflation, thereby eliminating much of the output stabilization costs that would otherwise be associated with reversing deviations of the price level from its target.

These results are robust to variations in parameter values and the specifications of output dynamics and price dynamics, but the characteristics of efficient policy rules depend critically on the assumption regarding expectations formation. Under rational expectations, efficient policies take advantage of the expectations channel through which anticipated future policy actions feedback onto the present. In backward-looking models, where expectations are policy-invariant functions of observable variables, this expectations channel is shut off and policies that, under rational expectations, rely on the effects of anticipated movements in short-term interest rates typically perform poorly. This is found to be true in both the backward-looking version of FRB/US, as well as in other models with adaptive expectations such as that of Rudebusch and Svensson (1999); in fact, in the latter model, policy rules that react in a highly persistent manner and rules that target the price level can be destabilizing.

Policies that are efficient in the backward-looking models exploit predictable expectational errors inherent in such systems. Empirical evidence indicates that the FOMC has tended to respond in a gradual and persistent manner to changes in economic conditions (Rudebusch (1995), Clarida, Gali and Gertler (1997), and Sack (1998)). Given this historical pattern for monetary policy, the estimated reduced-form effect of a change in the real short-term rate on real GDP will be quite large. In estimated backward-looking models, agents implicitly expect policy reactions to be highly persistent, so a movement in the short rate translates into a sizable movement in the long rate and real output. The result of this is that small transitory movements in the funds rate—which under the expectations theory of the term structure have little effect on long-term bond rates and thereby output—have large real effects in simulations of estimated backward-looking models. As a result, in such models, effective policies are characterized by little or even negative intrinsic persistence in interest rates. In this way, they take advantage of the stabilizing influence of the perceived policy without actually carrying out the expected actions.

The remainder of the paper is organized as follows. The first section presents a brief description of the FRB/US model and summarizes some of its basic properties. Section II analyzes the characteristics of efficient simple monetary policy rules in FRB/US under rational expectations. Section III considers the sensitivity of these results to changes in parameter values and model specification. Section IV examines how the characteristics of efficient rules are affected by a change in the the assumption regarding expectations formation. Section V concludes.

I. The FRB/US Model

FRB/US is an estimated large-scale structural rational expectations model of the world economy that was developed by the staff of the Board of Governors as a replacement for the MPS model. The model is of the stock-flow type. The U.S. economy is modeled in considerable detail, while a small set of reduced form equations is used for aggregate measures of foreign GDP, prices, and interest rates. FRB/US is the product of several years of development and testing with the result that its dynamic and long-run properties accord well with those of the data. For example, model impulse responses generally match well those of small-scale VAR models and model second moments are reasonably close to those of the data (Brayton, Levin, Tryon and Williams 1997a). For more detailed accounts of the model's design and properties, see Brayton and Tinsley (1996), Brayton, Mauskopf, Reifschneider, Tinsley and Williams (1997b), and Reifschneider et al. (1999).

A. Model Design

In the model, households maximize lifetime utility and firms maximize the present discounted value of expected profits, subject to adjustment costs that hinder instantaneous adjustment of quantities following a change in fundamentals. To capture the inertia evident in many categories of spending and labor inputs, the generalized adjustment cost model of Tinsley (1993) is used. This specification differs from the standard quadratic adjustment model, in that it allows for the appearance of lagged growth rates in the estimated decision rules.

The model's wage-price block contains separate equations for the prices for domestic absorption, consumption goods, crude energy, non-oil import goods, oil imports, and labor compensation (the employment cost index). Dynamics of the domestic absorption price index and the employment cost index are specified following Tinsley's generalized adjustment cost approach mentioned above. Current price inflation is determined by the existing level of the markup over labor and energy costs, recent past inflation, expected future growth in factor costs, and the expected level of resource utilization, with high utilization putting upward pressure on prices. Similarly, compensation growth is determined by the existing level of the productivity-adjusted real wage, past compensation growth, expected future growth in prices and productivity, and expected conditions in the labor market, with low unemployment (relative to the NAIRU) putting upward pressure on compensation growth.

A key feature of the specification of price dynamics, shared by the variant of staggered price setting introduced by Buiter and Jewitt (1981) and empirically implemented by Fuhrer and Moore (1995), is intrinsic inertia in the inflation rate. This property is controversial (see the discussions of Fuhrer (1997b) and Rotemberg and Woodford (1997)) and contrasts sharply with that of the staggered price setting models of Calvo (1983) and Taylor (1980), and the quadratic adjustment cost model of Rotemberg (1982), each of which generates inertia in the price level but not the inflation rate, in the absence of serially correlated shocks. Overall, the FRB/US model can be characterized as a hybrid model that incorporates more intrinsic persistence in prices and output than "optimizing" rational expectations models such as those developed by Rotemberg and Woodford (1997), King and Wolman (1999), and McCallum and Nelson (1999), but significantly less intrinsic persistence than in traditional backward-looking models developed by Fair and Howrey (1996), Ball (1997), and Rudebusch and Svensson (1999).

Given the sluggish adjustment of prices, monetary policy influences the *real* short-term rate through changes in the nominal federal funds rate. Movements in the real short-term rate affect real long-term rates, the real value of wealth, and the real exchange rate according to standard arbitrage conditions. In particular, long-term real rates on government and corporate debt, which influence investment spending by firms and households, are described by the expectations theory of the term structure. The real value of corporate equities, a determinant of consumption and investment spending, depends on the real return to corporate debt. Uncovered interest rate parity links the expected change in the exchange value of the dollar, which affects import and export volumes and import prices, to the interest rate differential between the United States and other industrialized economies. In addition to these "standard" channels of the monetary transmission mechanism, allowance is made in the model for credit market imperfections that cause spending by households and firms to be "excessively" reliant on current income and cash flow, respectively.

B. Computing Model Moments

Much of the analysis of this paper involves computing unconditional second moments of aggregate variables. In order to make this computationally feasible, the model is log-linearized around sample means; the relevant dynamic properties of the model are virtually unaffected by this approximation. In its companion form, the linearized system is given by

$$E_t \sum_{j=-1}^{M} H_j x_{t+j} = G e_t, \tag{1}$$

where M is the maximum lead in the model, x_t is the vector of endogenous variables, and e_t is a mean-zero vector of serially uncorrelated random disturbances with finite second moments, $E(ee') = \Omega$. We estimate Ω using the equation residuals from 1966–95. The information set for expectations formation differs across sectors; in general, date t expectations in the financial sector incorporate knowledge of date t variables, x_t, but expectations in the other sectors are limited to date $t-1$ variables, x_{t-1}.

One equation in this system corresponds to the monetary policy rule,

$$i_t = z_t \theta, \; z_t \subseteq (x_t', x_{t-1}'), \tag{2}$$

where i_t is the federal funds rate, θ is the policy rule parameter vector, and z_t is the set of variables to which policy reacts. For a given specification of the policy rule, we solve for the saddle point rational expectations solution, if it exists, using the AIM algorithm developed by Anderson and Moore (1985). The reduced form representation of the solution is given by

$$x_t = A(\theta)x_{t-1} + B(\theta)e_t. \tag{3}$$

Note that in general the elements of the matrices A and B depend on the policy rule parameter vector θ. For notational convenience, we set all constants to zero so that the unconditional expectation of all variables is zero, $E(x) = 0$.

Given the reduced form solution, we (approximately) compute the unconditional variance-covariance matrix for x, $C_0 \equiv E(xx')$,

$$C_0 = \sum_{j=0}^{\infty} A^j B \Omega B' A'^j, \tag{4}$$

using the doubling algorithm of Hansen and Sargent (1998). This approach yields highly accurate answers more efficiently than does the standard method of stochastic simulations. Autocovariances are readily computed using the formula $C_j = A^j C_0$. On a Sun Ultra Enterprise 3000 computer—about as fast as an Intel Pentium II 300Mhz personal computer—the computation of the saddle path solution and the unconditional covariance matrix takes about 5 minutes for the FRB/US model.

C. Model Properties

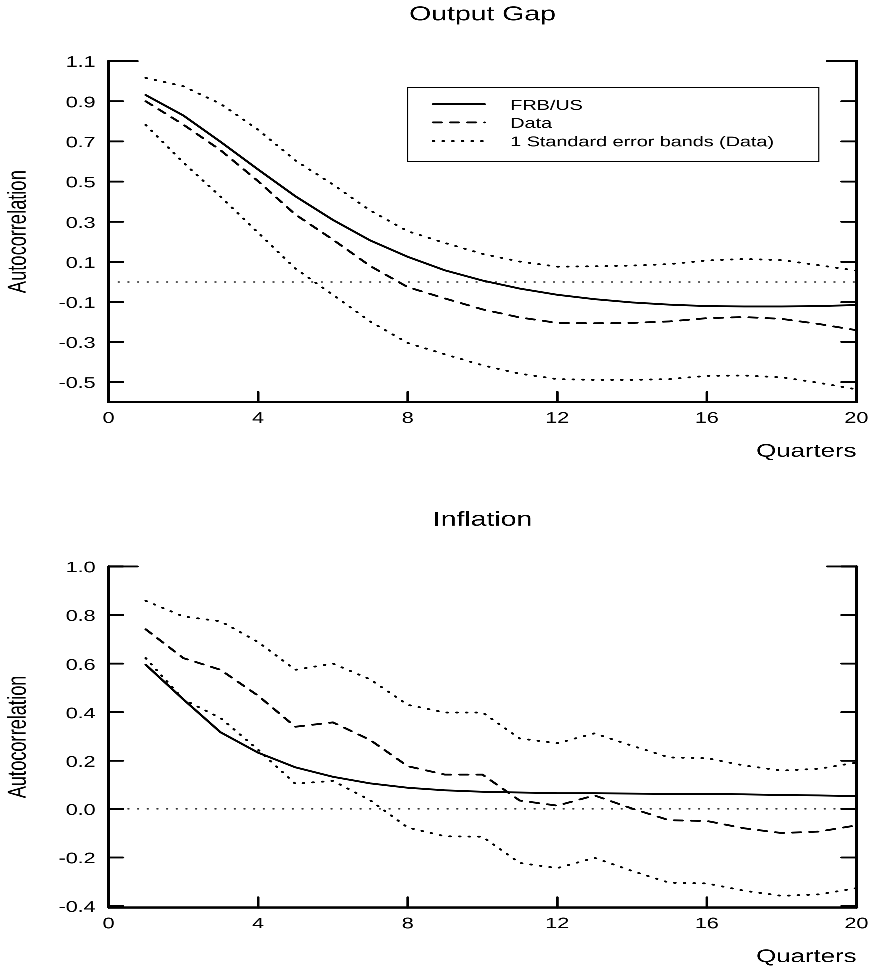
Detailed accounts of the dynamic properties of FRB/US are reported in the articles cited above. For present purposes, we use autocorrelations of inflation and output to summarize the degree of inertia present in FRB/US, and compare these outcomes to those found in the data. In computing model moments, we assume monetary policy follows a reaction function estimated over 1980–1997, given by

$$\begin{array}{rccccc} i_t = & -.16 & +.83\, i_{t-1} & +\, .38\, \pi_t^{(4)} & +\, .12\, y_t & +\, .77\, \Delta y_t, \\ & (.33) & (.06) & (.10) & (.07) & (.18) \end{array} \tag{5}$$

where $\pi^{(4)}$ is the four-quarter change in the personal consumption expenditures (PCE) price index and y_t is a measure of the output gap—the percent deviation of real GDP from its potential.[2] Standard errors are given in parentheses.

[2]The basic specification of this reaction function is identical to that in Orphanides and Wieland (1998), but, owing to differences in sample and the measure of the output gap, the estimated coefficients differ somewhat. It is worth noting that the large movements in inflation and output associated with 1980–82 disinflation help identify the inflation and output gap parameters in the reaction function. Dropping this period from the sample lowers the coefficients on the inflation rate and the change in the output gap, and causes the coefficient on the lagged funds rate to rise to about 0.9.

Figure 1: Autocorrelations of the Output Gap and Inflation



The solid lines in Figure 1 show the unconditional autocorrelations of the output gap and the inflation rate implied by the model, given the estimated reaction function. Unless otherwise noted, in this paper, "inflation" refers to the annualized one-quarter change in the PCE price index. The dashed lines show the estimated autocorrelations using quarterly data from 1980-97. The dotted lines show the one standard error bands for the data-based estimates. As seen in the top panel of the figure, the model's predictions for the autocorrelation of output closely track those found in the data. The model underpredicts somewhat the persistence of inflation relative to that seen in the data. Nevertheless, the differences are generally small in both the economic and statistical senses.

II. Policy Frontiers

We evaluate monetary policy rules using "policy frontiers" that measure the best obtainable pairs of unconditional variances of the output gap, σ_y^2, and the inflation rate, σ_π^2, subject to the constraint that the unconditional standard deviation of the funds rate, σ_i, does not exceed a specified value k. By varying k, we can draw the three-dimensional surface that represents the constraints the model places on the policymaker, in terms of the policy objectives of stabilizing inflation, output, and short-term interest rates. We refer to the policies that underly these frontiers as "frontier policies." Note that this approach differs from a common practice found in the literature, see, for example Rudebusch and Svensson (1999), where interest rate variability is included directly in the policy objective. The advantage of our approach is that one can analyze the constraints on policy independently of the preferences over the three types of variability.

Each point on a frontier corresponds to a different relative weight on inflation and output variability. Specifically, a frontier is computed by solving the minimization problem

$$\begin{aligned} \min_{\theta} \quad & \lambda\sigma_y^2 + (1-\lambda)\sigma_\pi^2 \\ \text{s.t.} \quad & x_t = A(\theta)x_{t-1} + B(\theta)e_t, \\ & i_t = z_t\theta,\ z_t \subseteq (x_t', x_{t-1}'), \\ & \sigma_i^2 \leq k^2, \end{aligned} \tag{6}$$

for values of λ on the unit interval. We restrict ourselves to policies that yield a saddle point equilibrium. The first constraint is that the law of motion of the system be given by the reduced form of the saddle point solution consistent with the specified policy rule. The second constraint is that the federal funds rate always be set according to the policy rule, which is assumed to be known by the public. The third constraint is that the unconditional variance in the funds rate does not exceed the specified value of k^2. Note that interest rate variability is measured by the variance of the *level* of the funds rate. The basic results from the FRB/US model are unchanged if interest rate variability is instead measured by the variance of the one-quarter *change* in the funds rate, as in Levin, Wieland and Williams (1999).

The constraint on interest rate variability plays an important role in the results presented below. According to the FRB/US model, if there were no constraint on interest rate variability, frontier policies would generate wild swings in the funds rate. The variability of interest rates has no direct effect on prices and quantities in the model. However, a number of reasons have been suggested why such volatility in short-term rates may be undesirable. One is political: Policymakers may wish to avoid reversals in the direction of policy out of the fear that such actions may be misinterpreted as "mistakes," which may eventually have consequences for central bank independence. A second argument is that the term premium paid on bonds may be positively related to the variance in expected short-term rates, in which case, there is a long-run tradeoff between the volatility of short-term interest rates and potential output through the effect of the term premium on the cost of capital and thereby the capital-output ratio (Tinsley 1998). This relationship is not incorporated in the FRB/US model. Third, the hypothesized invariance of model parameters to changes in policy rules is likely to be stretched to the breaking point under policies that differ so dramatically in terms of funds rate variability from those seen historically.

The general specification of policy rules analyzed in this paper bears comment. We allow policy to react to contemporaneous variables, an assumption McCallum (1997) has criticized on the grounds that policymakers do not in fact possess accurate information regarding the current state of the economy. Nonetheless, the results in this paper are unchanged if we assume policy can only react to lagged data. Levin et al. (1999) and McCallum and Nelson (1999) similarly find that enforcing a single-quarter lag to the policy response is not very important for the analysis of policy rules in rational expectations macro models. A potentially more difficult issue, not taken up in this paper, is the persistent mismeasurement of the output gap, as discussed by Orphanides (1998) and Rudebusch (1998). Another issue is the non-negativity constraint on nominal interest rates, which, in order to keep computational costs from becoming prohibitive, we ignore for most of this paper; we return to this topic at the end of this section.

A. Basic Characteristics of Frontier Policies

The first step in analyzing optimal simple policy rules is the choice of variables on the right-hand side of the reaction function. Evaluation of numerous candidate variables led to the selection of three main variables: the current level of the output gap, a multi-period measure of inflation, $\tilde{\pi}$, and the lagged funds rate. Mathematically, the class of policy rules we consider is given by

$$i_t = \theta_i \, i_{t-1} + (1-\theta_i)(r_t^* + \pi_t^{(4)}) + \theta_\pi(\tilde{\pi}_t - \pi^*) + \theta_y \, y_t, \tag{7}$$

where r^* is the long-run equilibrium real interest rate, $\pi^{(4)}$ is the four-quarter inflation rate, and π^* is the inflation target (assumed to be fixed). A necessary condition for policy to be stabilizing is that $\theta_\pi > 0$. We assume the policy rule is followed exactly; hence, the inclusion of the lagged funds rate is identical to specifying the rule in terms of the level of the funds rate responding to a weighted sum of current and past output gaps and deviations of inflation from target.

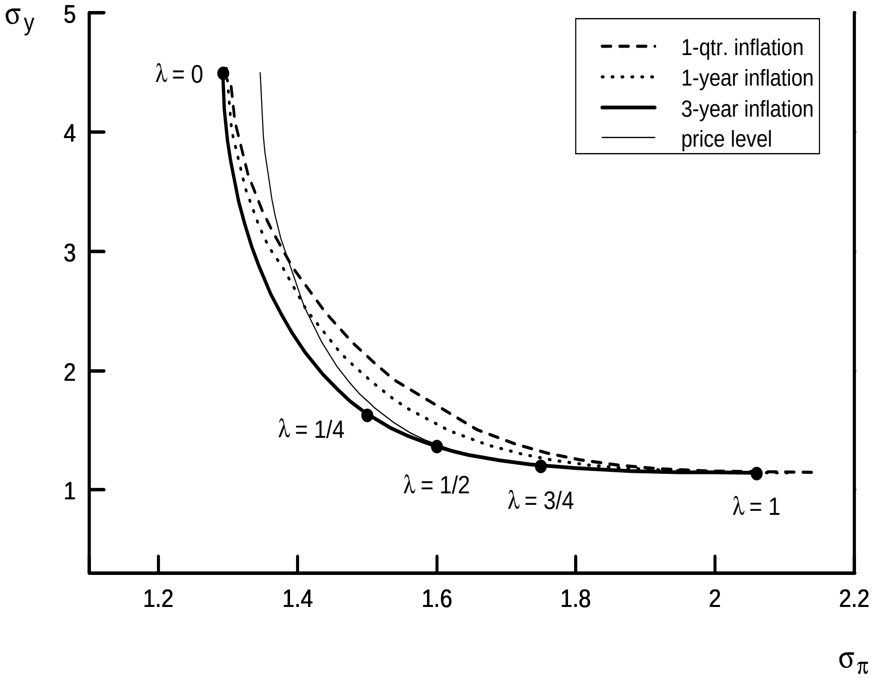
As noted, we find that the current output gap is the best choice for a single variable to measure resource utilization, in terms of the design of simple policy rules. Candidate measures of utilization that do not fair as well include the unemployment rate, which tends to be a lagging indicator relative to the output gap, the change in the output gap, or, similarly, the growth rate of real GDP, which ignores useful information on the level of resource utilization, and multi-period averages of the output gap.

The best choice of a measure of inflation for inclusion in the policy rule is generally not the current quarter's inflation rate. Instead, according to the FRB/US model, policy should in general respond to a much "smoother" measure of inflation, specifically, the growth rate of prices over the last three years. This measure of inflation evidently filters out the high frequency noise in the inflation process, leaving policy to react to sustained movements in inflation or "core" inflation. By reacting to a smooth inflation measure, policy implicitly purchases a reduction in output and funds rate variability at the cost of some high frequency variability in inflation.

Figure 2 shows policy frontiers resulting from different choices for the measure of the multi-period inflation rate $\tilde{\pi}$ appearing in the policy reaction function. Here, and throughout this paper, policy frontiers are displayed in terms of the standard deviation of the annualized one-quarter inflation rate, σ_π, and the standard deviation of the output gap, σ_y. For each frontier in Figure 2, the standard deviation of the funds rate is constrained to be less than or equal to 4, with the constraint binding in each case. As an aid in interpreting the figures, reference values of λ are indicated for the frontier corresponding to frontier rules that respond to the three-year inflation rate.

Except in the extreme cases in which the weight on output variability is near

Figure 2: Policy Frontiers and the Measure of Inflation in the Reaction Function



zero or unity, reacting to the three-year inflation rate yields nontrivial improvements in stabilization over the one-quarter or one-year inflation alternatives. Lengthening the measure of inflation beyond three years causes stabilization performance to deteriorate. If the weight on output variability, λ, is near zero, policy has more freedom to counteract high frequency inflation movements and therefore the benefits of reacting to a smoothed inflation measure are diminished. At the other extreme, if the weight on output variability is near unity, the coefficient on the inflation gap is very close to zero, so the choice of inflation measure is irrelevant.

A related result is the good performance of frontier price level targeting rules, that is, rules that react to deviations of the price level from a predetermined deterministic trend, shown by the thin solid line in Figure 2. Price level targeting rules outperform, in terms of *inflation* and output stabilization, rules that react to the one-year inflation rate for values of $\lambda > 0.1$, and perform nearly as well as rules that react to the three-year inflation rate for values of $\lambda > 1/2$. This result may appear surprising given the fact that under a price level targeting rule, any movement in inflation must be fully *reversed* over time; that is, the cumulative deviations of inflation from the target price growth rate must be zero. For example, following a positive shock to inflation, policy must act to bring the inflation rate *below* trend: The inflation rate must overshoot its long-run target level. In an inflation-based rule regime, policy only needs to bring inflation back on track, so the policy response, and the associated reduction in resource utilization, can be more muted than in the case of price level targeting (Lebow, Roberts and Stockton 1992).

In forward-looking rational expectations models such as FRB/US, the conventional wisdom regarding a policy of price level targeting can be misleading.[3] Some overshooting of inflation may be desirable owing to the effect of expected inflation on current inflation.[4] By construction, a price level targeting policy guarantees that the sum of future inflation rates equals the negative of the existing gap between the price level and the target. In general, this gap is positively related to the current inflation rate, so a price level targeting policy fosters expectations of below-trend inflation when inflation is high and the opposite when inflation is low. These expectations work to counteract the effects of inflation inertia in the model.

B. Coefficients of Frontier Policies

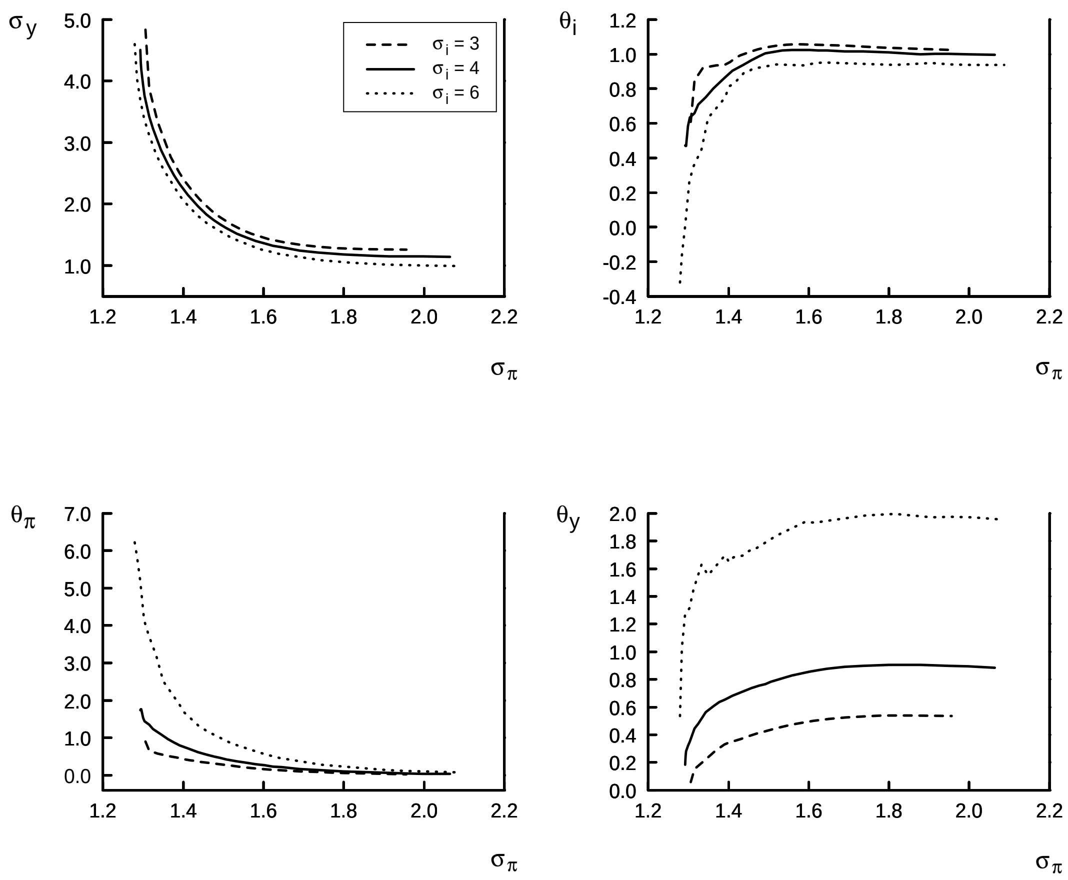
Unless otherwise indicated, we focus on rules where policy reacts to the three-year inflation rate for the remainder of the analysis using the FRB/US model. The upper left panel of Figure 3 shows three policy frontiers, computed for values of $k = 3, 4$, and 6. As the constraint on interest rate variability is relaxed, the frontiers move inward toward the origin. These frontiers (along with those for larger values of k not shown in the figure) illustrate the degree of diminishing returns, in terms of output and inflation stabilization, to interest rate variability. Starting from a frontier policy corresponding to a moderate amount of interest rate variability, further increases in interest rate variability yield only modest stabilization benefits.

The other three panels of Figure 3 show the parameter values of the frontier policy rules. To ease comparison to the frontiers, the horizontal axis in each panel of this figure measures the standard deviation of inflation; the vertical axis gives the coefficient value. Rightward movements along the curve correspond to increasing values of λ. As one would expect, the coefficient on inflation (the output gap) declines (rises) as the weight on output variability in the objective function increases,

[3]The conventional wisdom regarding the disadvantages of price level targeting has also been undermined by Svensson (1999b), who shows in a theoretical model that price level targeting can be more effective at stabilizing inflation and unemployment than inflation targeting if the monetary authority cannot commit to its actions in advance.

[4]The same principle applies to output dynamics, as discussed in Levin et al. (1999).

Figure 3: Policy Frontiers and Frontier Policies



and both the inflation and output gap coefficients increase as the constraint on interest rate volatility is relaxed. A more striking result is the large coefficient on the lagged funds rate, θ_i, in frontier rules. Indeed, except for cases where λ is close to zero, θ_i is very close to, or in some cases even exceeds, unity. This result is even stronger if the frontiers are computed using policy rules that react to the one-year, not three-year, inflation rate; in that case, for $k = 4$, $\theta_i = 0.85$ for $\lambda = 0$, and θ_i equals or exceeds unity for all values of $\lambda > 0.15$.

The result that frontier rules generally smooth the interest rate reaction to changes in economic conditions stems fundamentally from the constraint on the variability of the short-term interest rate (see Levin et al. (1999) for a more complete analysis of this issue). FRB/US incorporates the expectations theory of the term structure; hence, a small and persistent expected rise in the funds rate achieves the same change in the bond rate as one that is large, but short-lived. Given a desire to avoid fluctuations in short-term rates, the efficient response to an undesired increase in output or inflation is to hold the funds rate at an elevated level for an extended period of time (Goodfriend 1991). Given this policy response, the expectation of high future short rates has the desired effect on the bond rate and the level of resource utilization, while fluctuations in the funds rate are held to a minimum.

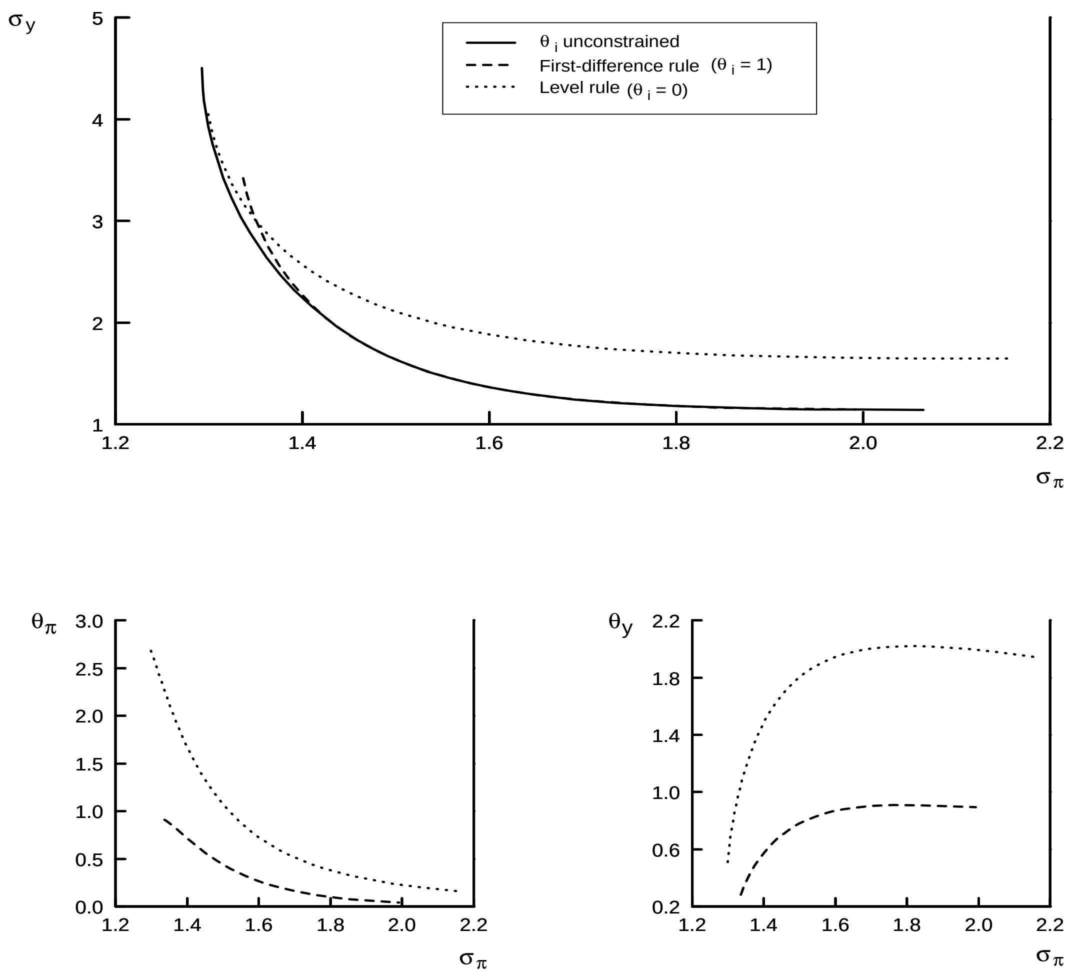
One potential disadvantage to policy rules with values of θ_i near unity is that, even if the *change* in the funds rate is in the right direction, the *level* of the real funds rate may not be appropriate for the current state of the economy. For example, if resource utilization is high for a period of time, the real funds rate will rise above its long-run equilibrium level. In the absence of further disturbances, resource utilization will return to its equilibrium level; however, at that point in time, the real funds rate will still be exerting a contractionary impetus, causing the economy to overshoot. To the extent that such overshooting is excessive and reduces stabilization performance, it counteracts some of the benefits of smoothing interest rate responses discussed above. This interaction of the costs and benefits of smoothing interest rate movements is illustrated by the upper right panel of Figure 3, which shows that relaxation of the constraint on interest rate variability—which diminishes the benefits of smoothing interest rates—reduces the value of θ_i in frontier policies, but generally by only a small amount.

Given that the value of θ_i is near unity for many frontier rules, it is of interest to measure the performance of the class of "first-difference" rules for which θ_i is constrained to equal unity. Figure 4 compares the outcomes from such first-difference rules to those for which θ_i is freely chosen; in both cases the frontiers are computed under the (binding) constraint that $\sigma_i \leq 4$. Not surprisingly, given the results from above, the loss from simplifying the rule to have a value of θ_i equal to unity is generally trivial. Only in cases where the policy objective places very little weight on variability of the output gap does the restriction cause a noticeable deterioration in stabilization performance. The figure also shows the frontier for policies where θ_i is constrained to equal zero. Except for cases where λ is near zero, such "level" rules perform worse than first-difference rules.

C. Adding Additional Information to the Policy Rule

FRB/US contains hundreds of variables representing prices and quantities in the goods, labor, financial, and foreign markets. Up to this point, we have focused

Figure 4: First-difference Rules vs. Level Rules



on very simple policy rules with no more than three variables. Abstracting from the claimed benefits of parsimony, optimal control theory argues that policy should respond to all the states of the system. Nevertheless, after considerable experimentation, we find that four-, five-, and six-parameter frontier rules yield only trivial gains over three-parameter frontier rules in minimizing the variances of output and inflation. For example, adding coefficients on combinations of lagged inflation rates, output gaps, or funds rates yields no measurable improvement in stabilization performance. Similarly, we found only trivial gains from including equity or bond prices or spending components to the policy rule. According to the model, the current output gap, a multi-period inflation rate, and the lagged funds rate are sufficient statistics for setting monetary policy. Admittedly, it may be the case that policies that react to a much larger set of variables outperform simple three-parameter rules; however, as argued in Levin et al. (1999), policies that are so finely tuned to a specific model's structure may be a poor guide to policy if the model is misspecified.

D. The Zero Bound on Nominal Interest Rates

In an environment of low inflation, linear policy rules can prescribe interest rates well below zero (Fuhrer and Madigan (1997) and Orphanides and Wieland (1998)). As noted, throughout most of this paper, we do not explicitly incorporate the non-negativity constraint on nominal rates into the policy rule. Here, we briefly summarize some relevant results from Reifschneider and Williams (1999), which analyzes the effects of the zero lower bound on the performance and design of monetary policy rules in FRB/US. We focus on the effect of imposing the zero bound on the outcomes from first-difference frontier policy rules computed under the constraint that $\sigma_i \leq 4$.

In the absence of the zero bound (or some other factor that causes policy to deviate from the rule), the first-difference specification can equivalently be written as one in which the *level* of the funds rate reacts to the sum of current and past gaps. In the context of the zero bound, however, these two descriptions are not identical because under the first-difference specification any past constraint on the funds rate is perpetuated through policy's response to the lagged funds rate. Indeed, simulations indicate that under unmodified first-difference specifications, the detrimental effects of the zero bound can be quite substantial. For this reason, it is important that policies be specified such that the level of the funds rate responds to cumulative past inflation and output gaps, not the lagged funds rate.

The frequency and magnitude of prescribed violations of the non-negativity constraint are negatively related to the equilibrium nominal interest rate—the sum of the equilibrium real rate plus the inflation target—which we denote by i^*. In the FRB/US model, for values of i^* of 5 and above, the zero bound has only trivial effects on the performance of frontier first-difference policy rules. A reduction in i^* from 5 to 4—a reduction in the inflation target of one percentage point—results in a very small increase in the variability of inflation and output. The marginal stabilization cost rises as the equilibrium nominal funds rate is lowered further. Nevertheless, even with a value of i^* of 2, a level consistent with zero or slightly negative long-run inflation, the stabilization cost due to the effects of the zero bound are relatively small, on the order of the shift in the frontier shown in Figure 3 that results from lowering the constraint on σ_i from 6 to 3.

Why is the cost from the zero bound so small for first-difference frontier policies? One reason is that these rules, when specified in terms of reacting to cumulative past inflation and output gaps, implicitly take into account past constraints on policy. Because the current setting of the funds rate depends on all past output and inflation gaps, policy tends to be easy—relative to the level dictated by current conditions alone—in the periods following a contraction. Anticipation of this behavior causes long bond rates to decline during a contraction even while the current funds rate is constrained to be zero.

III. Parameter and Model Uncertainty

A frequent criticism of model-based policy evaluation is that it is by its nature model-specific (McCallum 1988). Considerable uncertainty exists regarding parameter estimates and the appropriate specification of model equations. In this section, we entertain a number of issues related to parameter and model uncertainty. We find that the basic results regarding the design of efficient policy rules are robust to uncertainty regarding key parameter values and the specification of price and output dynamics.

A. Parameter Uncertainty

Because the FRB/US model contains literally hundreds of estimated coefficients, it is computationally prohibitive to conduct a complete analysis of the effects of parameter uncertainty on the characteristics of frontier policies. Nevertheless, the FRB/US model can be viewed as a disaggregated version of a small-scale rational expectations structural model. Two key parameters for the design of monetary policy in such a small model are the interest-sensitivity of aggregate demand and the sensitivity of inflation to movements in resource utilization (the slope of the Phillips curve).[5] To capture these general categories of parameter uncertainty, we vary the coefficients on the cost of capital terms in the spending equations and the coefficients on the gap between the unemployment rate and the NAIRU in the

[5]A third important factor is the speed of adjustment of spending and prices. Analysis of this factor is more involved than that conducted here. The results from the model uncertainty exercise in Levin et al. (1999) and summarized below, however, provide some insight into this aspect of parameter uncertainty.

wage and price markup equations. All other model parameters and the variance-covariance of the model residuals are left unchanged.

For the study of the effects of parameter uncertainty, it is useful to explicitly incorporate interest rate smoothing into the objective function. For this purpose, we modify our approach and compute "optimal" policies that solve the problem

$$\begin{aligned} \min_{\theta} \quad & \lambda\sigma_y^2 + (1-\lambda)\sigma_\pi^2 + \psi\sigma_i^2 \\ \text{s.t.} \quad & x_t = A(\theta)x_{t-1} + B(\theta)e_t, \\ & i_t = z_t\theta,\ z_t \subseteq (x_t', x_{t-1}'), \end{aligned} \tag{8}$$

where $\psi \geq 0$ measures the degree of aversion to interest rate variability. We continue to focus on three-parameter policy rules. To make the results comparable to those reported above, we set $\psi = 0.01$, which yields an unconditional standard deviation of the funds rate of about 4 under the optimal rule for $\lambda = 1/2$.

Our approach to incorporating parameter uncertainty into the computation of optimal policies follows that of robust control (Hansen and Sargent 1997). Instead of computing optimal rules for a specified distribution of model parameters, we simply posit a region within which the parameters may lie. The robust control policy rule minimizes the worst possible outcome over the specified parameter region. For present purposes, we define the allowable parameter region to include model coefficients relating to the interest-sensitivity of spending that lie within two standard errors of their point estimates and coefficients relating to the slope of the Phillips curve that lie within one standard error of their point estimates.[6]

The upper portion of Table 1 shows the optimal simple rules for five values of λ, assuming no parameter uncertainty. The lower portion of the table shows the corresponding robust control simple rules. The "worst" constellation of parameter values is the one where both the interest-sensitivity of demand and the unemployment-sensitivity of inflation are at the lower bounds of their respective allowable regions; that is, the worst-case scenario is one where policy is relatively ineffective, both directly at affecting demand, and indirectly, through the effect of resource utilization on inflation. The response of the robust control policy to the current output gap and inflation rate is weaker than the simple optimal policy, but, except for the

[6]The choice of two standard error bands for the coefficients relating to the interest-sensitivity of demand reflects the greater precision with which these coefficients are estimated relative to the coefficients relating to the slope of the Phillips curve, the t-statistics of which are below 2.

Table 1: Optimal Policies under Parameter Uncertainty

λ	θ_i	θ_π	θ_y	σ_π	σ_y	σ_i
Standard optimal simple rule						
0.00	0.77	0.56	0.06	1.31	4.57	2.57
0.25	1.03	0.31	0.66	1.54	1.54	3.61
0.50	1.01	0.24	1.02	1.64	1.27	4.33
0.75	0.98	0.18	1.42	1.77	1.12	5.06
1.00	0.94	0.04	1.87	2.25	1.00	5.93
Robust control simple rule						
0.00	0.94	0.37	0.04	1.34	9.58	3.37
0.25	1.10	0.13	0.31	1.77	1.82	2.75
0.50	1.03	0.14	0.67	1.91	1.48	4.06
0.75	0.98	0.12	1.06	2.08	1.28	5.14
1.00	0.93	0.03	1.49	2.71	1.13	6.26

case of $\lambda = 1$, the larger coefficient on the lagged funds rate implies that the robust control response is more persistent. The concern that policy may be relatively ineffective—that is, large fluctuations in interest rates are needed to move output and inflation—leads to a substitution towards policies that contain fluctuations in interest rates at the cost of greater variability in inflation and output.

The result that policy is more timid under robust control is the opposite of that of Stock (1999) who finds that robust control policies are more aggressive in the context of the small-scale backward-looking model developed by Rudebusch and Svensson (1999). The key issue is the tradeoff between inflation/output stabilization and a desire to minimize fluctuations in interest rates. The reduction in policy effectiveness creates both a "substitution" and an "income" effect. The income effect is related to the worsening of the outcome under the optimal control rule owing to the diminished effect of interest rate movements on output and inflation. The substitution effect is related to the reduced effectiveness of a given movement in the funds rate at affecting output and inflation. In FRB/US the substitution effect dominates for the examples considered here; as a result, a concern for parameter uncertainty tends to strengthen the desirability of a high degree of interest rate smoothing (large value of θ_i).

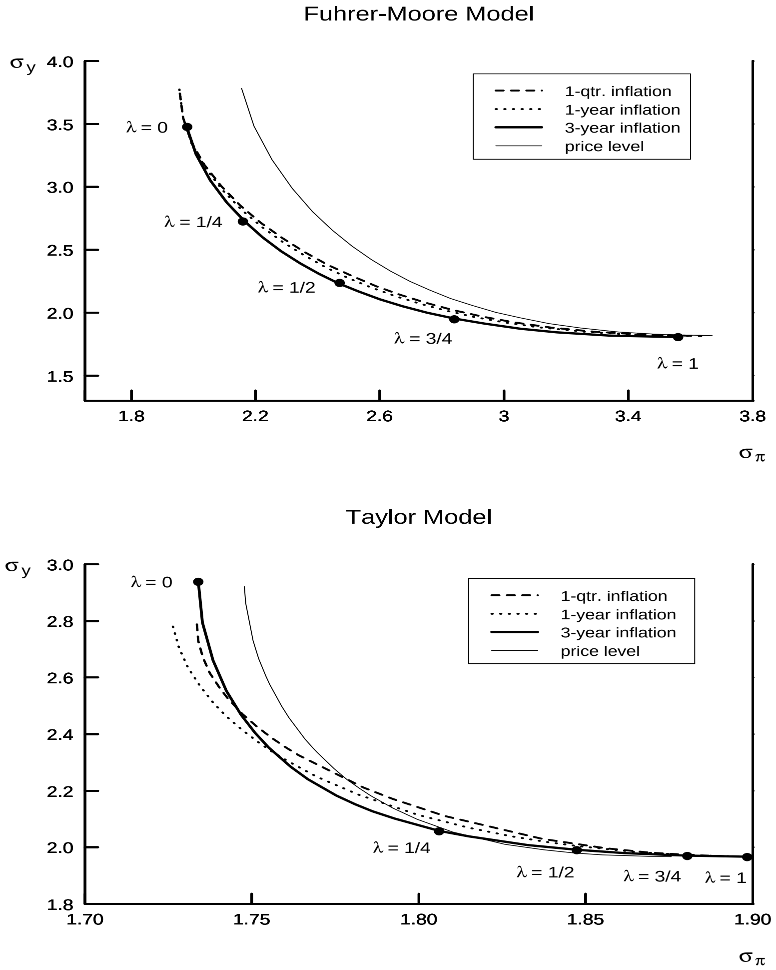
B. Model Uncertainty

Uncertainty regarding models goes beyond the estimation of certain macroeconomic relationships. The FRB/US model represents just one particular set of choices regarding model design and specification. Levin et al. (1999) examine the effects of different features of model design and specification by computing policy frontiers for the FRB/US, Fuhrer and Moore (1995), Taylor (1993b), and Orphanides and Wieland (1998) models. The constraint on interest rate volatility is given in terms of the variance of the first-difference of the funds rate, but otherwise the methodology is the same as in the present paper. Each of these models belong to the class of estimated structural rational expectations models. Nonetheless, the specification of the dynamics of real activity and prices differ significantly across models, particular in terms of the persistence of output and inflation. In all four models, in the preferred specification for simple (three-parameter) rules, policy reacts to the lagged funds rate, current output gap, and a multi-period measure of inflation. For moderate degrees of interest rate variability, all four models prescribe coefficients close to unity on the lagged funds rate for frontier rules. Indeed, a striking result is that simple frontier rules from FRB/US are found to be highly efficient in the three other models.

One issue not explicitly addressed in Levin et al. (1999) is the optimal choice for the duration of the multi-period inflation rate included in the policy rule and the cost, in terms of output and inflation volatility, of targeting the price level vs. the inflation rate. Figure 5 shows frontiers for the Fuhrer-Moore model and a linearized version of John Taylor's multicountry model, computed in the same manner as Figure 2 is for FRB/US.[7] The basic results regarding the choice of the duration of the inflation measure in the policy rule are the same in these models as in FRB/US. One minor difference is that in the Taylor model, policies that react to the one-year inflation measure slightly outperform those that react to the three-year inflation measure if λ is near zero. In all three models, the stabilization costs associated with switching from a frontier inflation targeting rule to a frontier price level targeting rule are modest.

[7] I thank Jeff Fuhrer and John Taylor for providing detailed information on the equations and residuals of their models.

Figure 5: Reacting to Different Inflation Measures in Other RE Models



IV. Expectations Formation

A key assumption of the preceding analysis is that expectations are consistent with the model structure and the policy rule in place. A number of authors have used backward-looking models, that is, models where the expectations process is invariant to the policy rule, for policy rule evaluation (Fair and Howrey (1996), Ball (1997), and Rudebusch and Svensson (1999)). The characteristics of frontier or optimal policies in such models can differ significantly from those computed from FRB/US and other structural rational expectations models. These discrepancies may be in part due to other differences in model design and specification. To address this issue, we examine the performance of policy rules in a version of FRB/US in which expectations are assumed to be formed using a fixed VAR model of the economy. In this way, we are able to modify the assumption regarding the formation of expectations, while holding the remaining model structure fixed.

For this exercise, we compute outcomes for five representative policy rules. Table 2 gives the coefficients based on the specification

$$i_t = \theta_i \, i_{t-1} + (1 - \theta_i)(r_t^* + \pi_t^{(4)}) + \theta_\pi(\pi_t^{(4)} - \pi^*) + \theta_y \, y_t + \theta_{\Delta y} \, \Delta y_t. \tag{9}$$

The first line in the table corresponds to the estimated reaction function reported in equation 5. The second and third lines represent "level" rules that have been discussed extensively in the literature. The fourth rule is a representative first-difference rule. The final rule is a representative frontier price level targeting rule; in this specification, the inflation gap, $(\pi^{(4)} - \pi^*)$ is replaced by the four-quarter average of the price level gap, $\frac{1}{4}\sum_{i=0}^{3}(\log P_{t-i} - \log P_{t-i}^*)$, where P is the level of the PCE price index and P^* is its predetermined target value.

Table 2: Policy Rule Comparisons

	θ_i	θ_π	θ_y	$\theta_{\Delta y}$
Estimated (1980-97)	.83	.21	.12	.77
Henderson and McKibbin (1993)		1	2	
Taylor (1993a)		.5	.5	
First-difference	1	.5	.5	
Price level targeting	.95	.4	.9	

A. FRB/US with VAR-based Expectations

Table 3 reports the outcomes—the unconditional standard deviations of inflation, the output gap, the funds rate, and the change in the funds rate—resulting from the five rules in FRB/US under two alternative assumptions regarding expectations formation. The upper set of outcomes are computed under the assumption of rational expectations. The lower set of outcomes are computed under the assumption that firms and households use vector autoregressive models to forecast relevant macroeconomic prices and quantities. The VAR models used for forecasting are estimated on the actual historical data, but are assumed to be invariant to changes in the policy rule for this analysis: private agents forecast with the same VAR regardless of the policy rule.

Table 3: Policy Rule Outcomes under Alternative Expectations Assumptions

	σ_π	σ_y	σ_i	$\sigma_{\Delta i}$
Rational expectations				
Estimated (1980-97)	1.59	2.81	2.55	0.95
Taylor (1993a)	1.86	2.92	2.51	0.90
Henderson and McKibbin (1993)	1.89	1.75	4.32	2.00
First-difference	1.53	1.76	3.22	0.77
Price level targeting	1.55	1.51	4.03	1.04
VAR-based expectations				
Estimated (1980-97)	1.72	1.70	1.87	0.80
Taylor (1993a)	1.63	1.85	2.07	0.94
Henderson and McKibbin (1993)	1.57	1.23	2.52	2.07
First-difference	2.20	3.49	5.68	2.18
Price level targeting	1.94	2.34	4.08	1.81

Two aspects of these results are noteworthy. First, switching from rational expectations to VAR-based expectations reverses the relative performance of "level" and "first-difference" rules in FRB/US. In the policy reaction function that makes up part of the VAR model used for forming expectations, the sum of the coefficients on the lagged funds rate is about 0.95 and the sums of the coefficients on the inflation and output gaps are less than 0.1. Agents assume that movements in the funds rate will be highly persistent, but not as persistent as in first-difference rules. Hence, under the first-difference rule, the public systematically underpredicts the size and persistence of the policy response to aggregate disturbances, making such policies less effective than is the case under rational expectations. Under level rules, such as the Taylor (1993a) and Henderson and McKibbin (1993) rules, the public systematically overpredicts the persistence of the policy response, with the result that such policies are more effective than in the absence of this policy misperception. Similarly, price level targeting involves a significantly larger loss in stabilization under VAR-based expectations. The public uses a forecasting model based on a regime of inflation targeting, which shuts off the stabilizing effects of the expectations

Table 4: Outcomes in the Estimated Small-scale Backward-looking Model

	σ_π	σ_y	σ_i	$\sigma_{\Delta i}$
Estimated (1980-97)	3.00	4.13	7.02	0.95
Taylor (1993a)	2.16	4.32	6.05	0.84
Henderson and McKibbin (1993)	1.79	3.57	5.99	2.04
First-difference	16.15	7.07	34.12	7.67
Price level targeting	∞	∞	∞	∞

channel discussed above. The estimated rule is not efficient under either of the two assumptions regarding expectations, but performs reasonably well in both cases.

B. An Estimated Small-scale Backward-looking Model

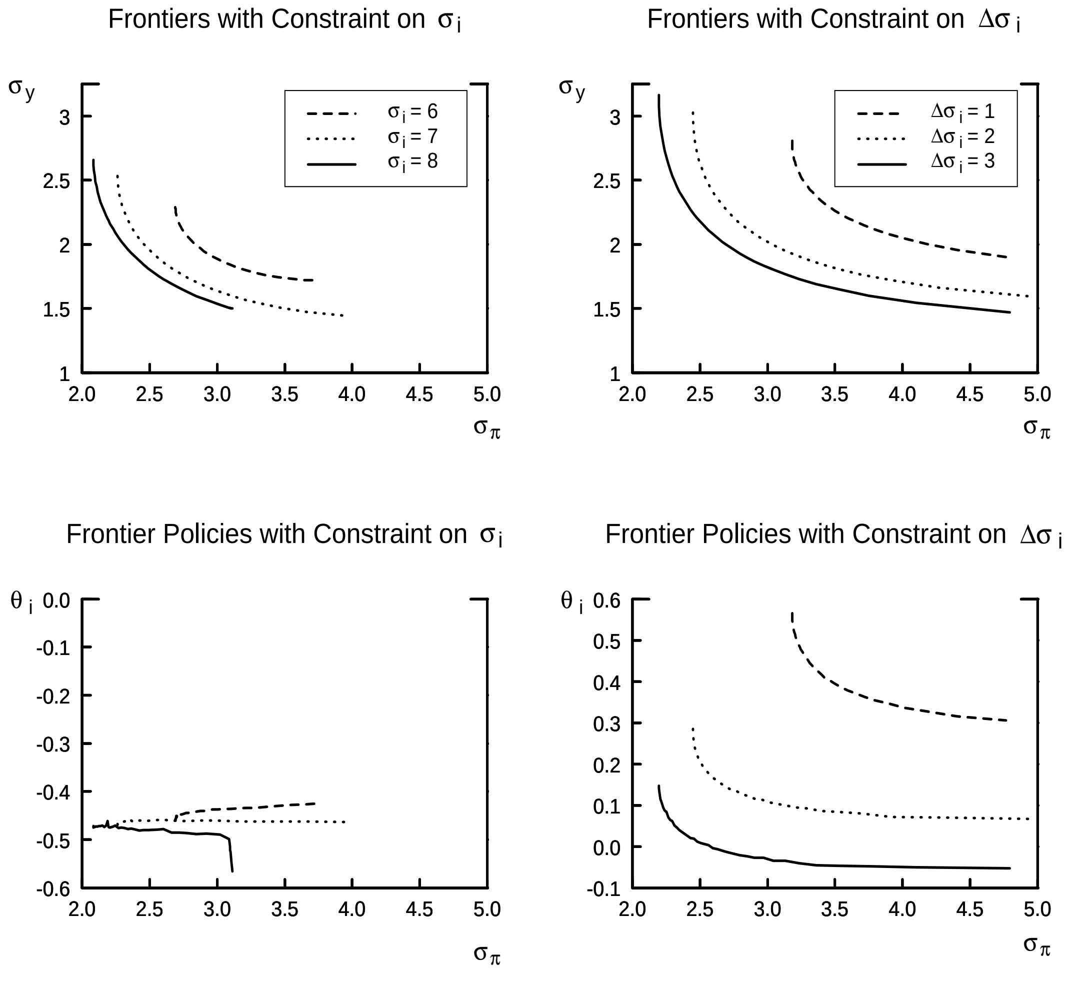
The contrast in outcomes relating to expectations formation is even more dramatic if an estimated small-scale backward-looking model is used in place of FRB/US under VAR-based expectations. To illustrate this point, we evaluate the performance of policy rules and compute frontiers using a model similar to that of Rudebusch and Svensson (1999). The model consists of three equations: a dynamic IS curve relating the output gap to the level of the real funds rate and lags of the output gap, an accelerationist Phillips curve, and the monetary policy rule. Model details are given in the appendix.

Table 4 shows the outcomes from this estimated backward-looking model for the policy rules described in Table 2. The most striking finding is the abysmal performance under both the first-difference and the price-level targeting rules. The economy is barely stable under the first-difference rule; the price-level targeting rule is in fact destabilizing, indicated by the unconditional moments being infinite.[8] These results generalize to other parameterizations of first-difference and price level targeting rules. The poor performance of these types of policies is related to the existence of a strong accelerator effect in output and the fact that output reacts to the real *short-term* interest rate. Movements in the funds rate that are highly persistent, owing either to large values of θ_i or attempts to reverse inflation shocks,

[8] These results mirror those of von zur Muehlen (1995), who showed using a simple macro model that interest rate smoothing policy rules that are stabilizing if expectations are forward-looking can be destabilizng if inflation expectations are backward-looking.

cause output to overshoot dramatically, which can lead to dynamic instability. The same does not occur in the FRB/US model under VAR-based expectations, in part because, in that model, output responds primarily to long-term interest rates which only partially respond to current short-term rates.

Figure 6: Policy Frontiers for the Estimated Backward-looking Model



The characteristics of three-parameter frontier policies in this model depend on how interest rate variability is measured. The left panels of Figure 6 show the outcomes when the constraint on funds rate variability is specified in terms of the variance of the *level* of the funds rate. In this case, frontier policies tend to have negative persistence, that is, $\theta_i < 0$; in fact, the value of θ_i is typically below -0.4. The efficient policy response to a shock is a sharp and quickly reversed movement of the funds rate. Such a policy move would have little effect on prices and output in a world where bond rates are determined by the expectations theory of the term structure and expectations are rational, but, in this model, the policy is very effective because it systematically takes advantage of the public's misperception of policy.

The right panels of the figure show the outcomes when the constraint is specified in terms of the variance of the *change* of the funds rate. In this case, efficient policies generally exhibit some inherent positive persistence with larger values of θ_i associated with tighter constraints on the variance of the change in the funds rate. In no case, however, are frontier policies characterized by values of θ_i close to unity. The difference between the results is explained by the fact that, in this model, the only transmission channel is the direct effect of movements in the real funds rate on output. Owing to the lagged responses of output and inflation, a policy that features quick reversals provides a timely countercyclical impulse to output without engendering overshooting. The downside to such a policy is that the funds rate jumps around from quarter to quarter, even if the unconditional variance is relatively low. Thus, when the constraint on policy is in terms of the change in the funds rate, policies with strong negative inherent persistence are abandoned in favor of those that generate less dramatic quarter-to-quarter swings.

V. Conclusion

In this paper, we evaluate classes of simple monetary policy rules using the FRB/US large-scale open-economy macroeconometric model. We find that simple policy rules are very effective at minimizing the fluctuations in inflation, output, and interest rates: Complicated rules yield trivial stabilization benefits over efficient simple rules. Efficient rules smooth the interest rate response to shocks and use the feedback from anticipated policy actions to stabilize inflation and output and to moderate movements in short-term interest rates. Policy should react to a multi-period inflation rate rather than the current quarter inflation rate. Indeed, targeting the price level—equivalent to an infinite horizon inflation rate—generates little additional cost in terms of output and inflation variability over that associated with inflation targeting policies. The effectiveness of efficient simple rules is little diminished by the imposition of the non-negativity constraint on nominal interest rates.

These results are robust to reasonable variations in parameter values and the specification of output and price dynamics. However, the characteristics of efficient policy rules depend critically on the assumption regarding expectations formation. Under rational expectations, efficient policies take advantage of the expectations channel through which anticipated future policy actions feedback onto the present. In backward-looking models, where expectations are implicitly policy-invariant functions of observable variables, policies that are efficient under rational expectations may perform poorly, and effective policies exploit systematic expectational errors.

Given the degree of model uncertainty, such a divergence of outcomes may argue against policies that are efficient under rational expectations but perform poorly under adaptive expectations (Taylor 1998). An alternative interpretation is that the results from backward-looking models are suspect for the very reason Lucas elucidated in his famous Critique; that is, "any change in policy will systematically alter the structure of econometric models" implying that "comparisons of the effects of alternative policy rules using current macroeconometric models are invalid regardless of the performance of these models over the sample period or in ex ante short-term forecasting" (Lucas (1976)). Backward-looking models may simply be ill-suited for the evaluation of the long-run properties of monetary policy rules that differ significantly from those experienced historically. This is not to say that such analysis is without merit or value. In the absence of a satisfactory description of the process by which policy expectations are formed and modified, policy evaluation based on backward-looking models may be relevant, especially for horizons of a few years, if adjustment of expectations formation to changes in policy is gradual. If, on the other hand, adjustment is rapid and the transition period during which agents update their expectations is short, the assumption of rational expectations may better approximate the environment facing policymakers at all horizons.

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Appendix

The specification of the simple backward-looking model discussed in section 5 of the paper is similar to that of Rudebusch and Svensson (1999). The main difference lies in the use of the consumption (PCE) price index instead of the GDP price index as the price variable. This change was made to make the analysis more closely correspond to that using the FRB/US model. Output gap dynamics are described by a simple error-correction equation relating the current change in the output gap to the lagged level of the output gap, two lags of the change in the output gap and the lagged value of the difference between the lagged two-quarter moving average of the expost "real" federal funds rate, $\tilde{r}_{t-1} = \frac{1}{2}(i_{t-1} + i_{t-2} - \pi_{t-1} - \pi_{t-2})$ and its long-run equilibrium level. Inflation dynamics are described by a version of the accelerationist Phillips curve in which the change in the inflation rate depends on two lags of the change in the inflation rate and the lagged value of the output gap.

Maximum likelihood estimation of these two equations over 1960–97 yields

$$\begin{aligned} \Delta y_t &= \underset{(.03)}{-.12}\, y_{t-1} + \underset{(.07)}{.20}\, \Delta y_{t-1} + \underset{(.08)}{.17}\, \Delta y_{t-2} - \underset{(.03)}{.10}\, (\tilde{r}_{t-1} - \underset{(.66)}{2.69}), \\ R^2 = .21, \quad \text{SER} &= .80, \quad \text{DW} = 1.95 \end{aligned}$$

$$\begin{aligned} \Delta \pi_t &= \underset{(.08)}{-.35}\, \Delta\pi_{t-1} - \underset{(.08)}{.30}\, \Delta\pi_{t-2} + \underset{(.04)}{.15}\, y_{t-1}. \\ R^2 = .18, \quad \text{SER} &= 1.15, \quad \text{DW} = 1.95 \end{aligned}$$