Nominal GDP Targeting and the Taylor Rule on an Even Playing Field

David Beckworth and
Joshua R. Hendrickson

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Abstract

Some economists advocate nominal GDP targeting as an alternative to the Taylor rule. These arguments are largely based on the idea that nominal GDP targeting would require less knowledge on the part of policymakers than a traditional Taylor rule. In particular, a nominal GDP targeting rule would not require real-time knowledge of the output gap. We examine the importance of this claim by amending a standard New Keynesian model to assume that the central bank has imperfect information about the output gap and therefore must forecast the output gap based on previous information. Forecast errors by the central bank can then potentially induce unanticipated changes in the short-term nominal interest rate, distinct from a standard monetary policy shock. We show that forecast errors of the output gap by the Federal Reserve can account for up to 13 percent of the fluctuations in the output gap. In addition, our simulations imply that a nominal GDP targeting rule would produce lower volatility in both inflation and the output gap in comparison with the Taylor rule under imperfect information.

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Author Affiliation and Contact Information

David Beckworth
Senior Research Fellow
Program on Monetary Policy, Mercatus Center at George Mason University
dbeckworth@mercatus.gmu.edu

Joshua R. Hendrickson
Assistant Professor of Economics
Department of Economics, University of Mississippi
jrhendr1@olemiss.edu

Nominal GDP Targeting and the Taylor Rule on an Even Playing Field

David Beckworth and Joshua R. Hendrickson

Some economists advocate nominal GDP targeting (Sumner 2011, 2012; Hendrickson 2012b) as an alternative to the Taylor rule. In short, the argument for a nominal GDP target is that it allows central bankers to focus on one variable rather than two; that it does not require the central bank to respond to real variables potentially beyond its control; and that by targeting nominal GDP the central bank does not have to try to distinguish, in real time, between shocks to aggregate supply and shocks to aggregate demand. Koenig (2012), however, argues that nominal GDP targeting is just a special case of a Taylor rule. If true, this implies that the choice between nominal GDP targeting and the Taylor rule is really just a choice about the optimal parameters of a policy feedback rule.

In this paper, we argue that a comparison of a nominal GDP targeting rule and a Taylor rule goes beyond the algebraic manipulation of a monetary policy rule, even if it is assumed that the operating procedures of policy remain the same.[1] Our argument is that the ability to algebraically manipulate a Taylor rule to obtain a nominal GDP targeting rule ignores critical information differences between these two different policy regimes. Nominal GDP is measured independently. Although it might be subject to measurement error, targeting nominal GDP growth likely minimizes the significance of this measurement error in real time. In contrast, measures of the output gap require estimates of both real GDP and potential GDP. This is further complicated by the fact that any real-time central bank estimate of potential GDP is likely a function of observed past values of real GDP, which are also subject to revision. This is problematic given the

[1] For an approach to nominal GDP targeting under different operating procedures, see Belongia and Ireland (2015).

evidence that the Federal Reserve's real-time estimates of the output gap have, at times, systematically differed from the actual gap (Orphanides 2000, 2002a, 2002b, 2004).[2]

Uncertainty about potential GDP implies that, when monetary policy is modeled for a central bank following a Taylor rule, the analysis should include an equation that describes how the central bank estimates potential GDP. This characteristic is important because it suggests that errors in the central bank's forecast of potential GDP can be a potential source of business-cycle fluctuations that would not exist under a nominal GDP targeting rule.[3] The basic idea is as follows. If the central bank adjusts the nominal interest rate in response to its own imperfect estimate of the output gap, there will be two types of monetary policy shocks. The first type is the traditional shock that represents a deviation of monetary policy from its rule. The second type is the forecast error of the central bank, which also causes the short-term interest rate to deviate from the perfect information rule. Under a nominal GDP targeting regime, policymakers need not worry about potential. Instead, changes in the trend of real GDP over time will be reflected in higher or lower inflation rates consistent with the central bank's nominal GDP target. By relieving the central bank of the need to estimate the output gap in real time, nominal GDP targeting can potentially reduce economic fluctuations because it eliminates monetary shocks from forecast errors.

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[2] The problem of identifying the natural level of output or the natural rate of unemployment is by now well known. On the natural rate of unemployment, see Staiger, Stock, and Watson (1997) and Laubach (2001). On the natural rate of output, see Orphanides and van Norden (2005) and Lansing (2002). As a result, Staiger, Stock, and Watson (1997) and Orphanides and Williams (2002) argue that interest rate rules should include changes in the unemployment rate rather than deviations from the natural rate. The approach in this paper is to suggest nominal GDP targeting as an alternative.

[3] A common criticism of this argument is that nominal GDP targeting also requires understanding something akin to a trend in real GDP. The foundation for this argument is that nominal GDP growth equals inflation plus real GDP growth. However, this fundamentally misunderstands the desirability of a nominal GDP target. It is wrong to think of nominal GDP growth as the sum of inflation and real GDP. Nominal GDP is a unique economic variable that is estimated independently of estimates or real GDP. In addition, it is the GDP deflator that is calculated as the implicit variable, not nominal GDP. Quantity-theoretic analyses of nominal GDP targeting recognize this point (Belongia and Ireland 2015).

The purpose of this paper is to argue that evaluating the desirability of a nominal GDP targeting rule relative to a Taylor rule requires that the actual information available to central bankers be taken into account in any model-based comparison. To accomplish this, we consider the implications for the variance of the output gap and inflation under both a Taylor rule and a nominal GDP targeting rule in the context of a standard New Keynesian model. Contrary to much of the previous literature, we assume that the central bank has imperfect information about the output gap. We estimate the model using Bayesian techniques. In doing so, we are able to estimate the size and persistence of the forecast error made by central banks using data from the Federal Reserve's Greenbook forecasts. We can then estimate conditional variance decompositions to determine what percentage of the fluctuations in the output gap are actually due to the central bank's forecast errors. Finally, we conduct simulations to compare the volatility of inflation and the output gap under both the Taylor rule and a nominal GDP targeting rule. We show that nominal GDP targeting reduces the volatility of the output gap and inflation in comparison to the case in which the central bank uses a Taylor rule with imperfect information about the output gap.

Our estimation results show that shocks to the central bank's forecast of the output gap can explain as much as 13 percent of the fluctuations in the actual output gap. In addition, our simulation results suggest that the variance of inflation is lower but that the variance of the output gap is higher under a nominal GDP target than it would be with the Taylor rule under the assumption that the central bank knows the output gap in real time. However, both the variance of inflation and the variance of the output gap are lower under a nominal GDP target than under the Taylor rule when the central bank has imperfect information about the output gap.

This paper is closely related to two other papers in the literature. Garín, Lester, and Sims (2016) focus on the relative roles of price and wage rigidities as they relate to nominal GDP targeting. These researchers find that nominal GDP targeting outperforms a Taylor rule and inflation targeting. In addition, they find that nominal GDP targeting performs best when wages are relatively more sticky than prices. Belongia and Ireland (2015) propose a way to target nominal GDP that is akin to the P-star model. They show that the central bank can use Divisia monetary aggregates to target nominal GDP. This provides a way for the central bank to implement a target for nominal GDP outside the interest rate reaction function approach common in the New Keynesian literature. Our paper adds to this literature by comparing and contrasting the Taylor rule with nominal GDP targeting, with a particular emphasis on the role of imperfect knowledge in the conduct of monetary policy.

Monetary Policy and the Output Gap

The Knowledge Problem and the Output Gap

One of the key challenges facing monetary policy authorities is the knowledge problem. As first noted by Hayek (1945), this problem arises because the information needed for optimal economic planning is distributed among many individual firms and households and therefore outside the knowledge of a central planning authority. This observation, when specifically applied to central banking, means that the information required to make activist countercyclical policies work is not available. Consequently, monetarists like Friedman (1953, 1968), Brunner (1985), and Meltzer (1987) argued early on against central bank discretion and instead called for simple rules that committed monetary authorities to stable money and nominal income growth.[4]

[4] Even if the knowledge problem could be overcome, Kydland and Prescott (1977) and Barro and Gordon (1983) show that central banks would still struggle with discretion because of the problem of time inconsistency. This insight also points to a need for monetary policy rules.

The knowledge problem is later shown by Orphanides (2000, 2002a, 2002b, 2004) to apply not only to central banks that conduct discretionary monetary policy but also to ones that follow a "constrained discretionary" approach to monetary policy. That is, even central banks that follow some kind of Taylor rule in a flexible inflation-targeting regime are susceptible to the knowledge problem.

To see why, consider a standard Taylor rule:

$$r_t = r_t^* + \phi_\pi \pi_t + \phi_y \tilde{y}_t, \qquad (1)$$

where r^* is the equilibrium nominal interest rate, π_t is inflation, $\tilde{y}_t$ is the output gap, and ϕ_π and ϕ_y are parameters.

Orphanides (2002a, 2002b) observes that the knowledge problem can arise in determining the response coefficients ϕ_π and ϕ_y and in choosing the correct measure for π_t.[5] The biggest information challenge, however, comes from attempting to measure the output gap, $\tilde{y}_t$, in real time. The output gap is the difference between the economy's actual and potential level of output and is subject to two big measurement problems. First, real-time output data generally get revised and often on the same order of magnitude as the estimated output gap itself. Second, potential output estimates are based on trends that rely on ever-changing endpoints. Orphanides finds the latter problem to be the biggest contributor to real-time misperceptions of the output gap. This means that even if real-time data improved such that there were fewer revisions, there would still be a sizable problem measuring the real-time output gap.

To illustrate these problems, figure 1 replicates Orphanides's (2002b) construction of real-time output gap measures using vintage real output data and compares them to final output gap measures using the Hodrick-Prescott and Baxter-King filters. We construct this figure by

[5] For example, should ϕ_π be based on current or forecasted values of inflation? If the latter, what is the appropriate forecast horizon?

taking the vintage real output data available for every quarter from 1965:Q1 to 2011:Q4 and applying the filters to the data. That is, for every quarter, a real-time estimate is made of the output gap given the data available through that quarter.[6] We then add all real-time output gap estimates for each quarter into one series and plot the series against the output gap created by using the final data available.

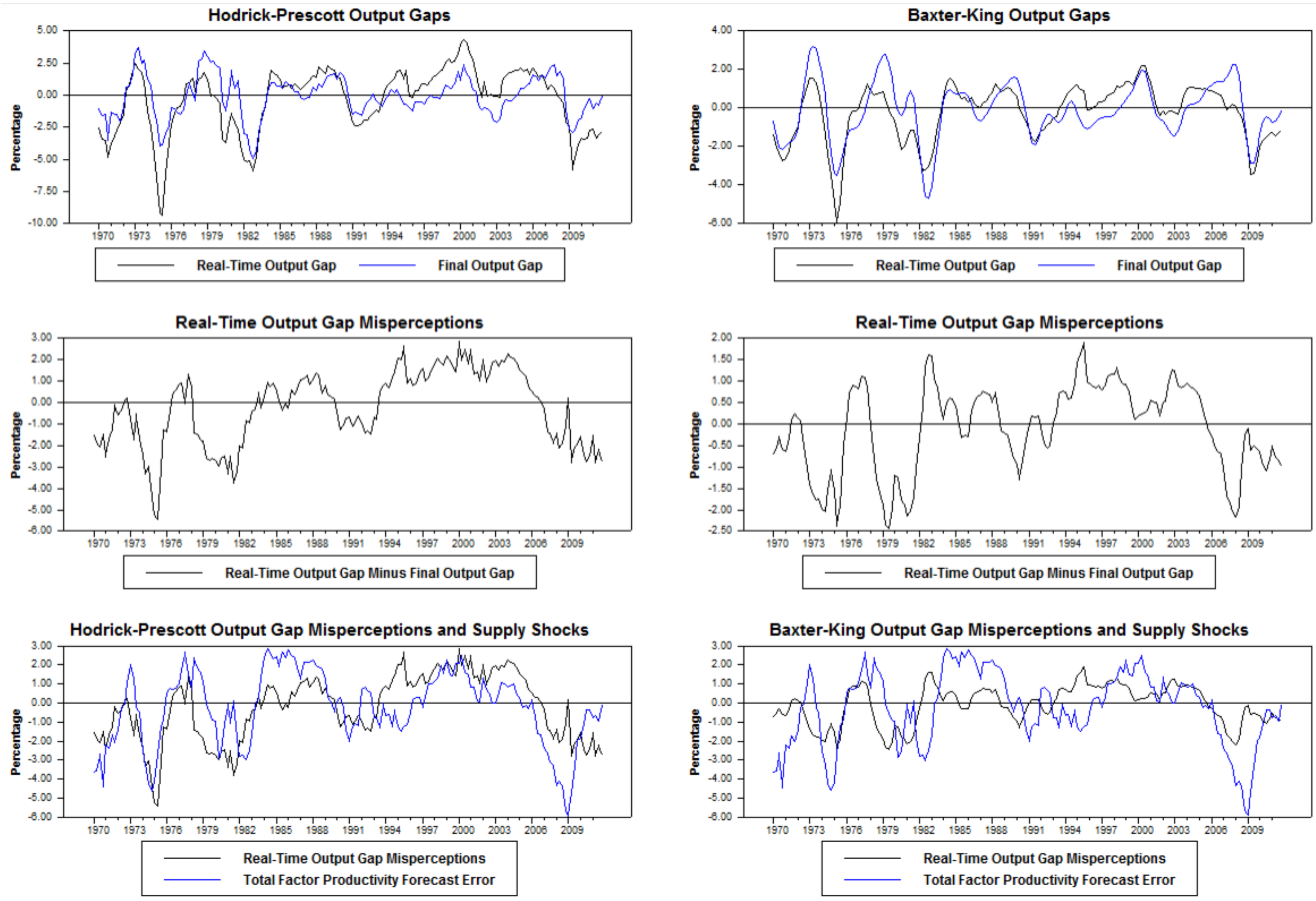
The top panel in figure 1 shows both the real-time and final output gap measures. To help discern how different these measures are, the second row plots the real-time output gap misperceptions, or the difference between the real-time and final output gaps. Both the Hodrick-Prescott and the Baxter-King filters reveal sizable measurement problems, particularly in the 1970s. The Hodrick-Prescott filter shows real-time output gap misperceptions reaching as much as 5 percentage points, while the Baxter-King filter shows up to 2 percentage points in the 1970s.

Orphanides (2004) sees these large measurement errors as a key contributor to the unmooring of inflation in the 1970s. He shows that, if the real-time estimates of the output gap and inflation from the 1970s are plugged into a Taylor rule like equation (1), the result is pretty close to the actual monetary policy that occurred during this time. The Great Inflation, in other words, was not the result of the Federal Reserve failing to properly respond to the economic developments of the time. It was the result of the Federal Reserve failing to properly measure the output gap.

Interestingly, figure 1 also indicates that the Great Moderation period of 1984–2007 was characterized by relatively smaller real-time output gap misperceptions. These findings raise

[6] Because these filters are sensitive to endpoints, we estimate the trend for each vintage quarter time series and then extrapolate ahead five years. This horizon is far enough out to get past the business cycle and arguably reflects where observers in real time expected trend real output to be headed. We add this forecasted path to the vintage real output series and apply the filters to it. This provides a better endpoint anchor. The vintage real output data come from the Philadelphia Federal Reserve Bank and consist of vintage real GNP information up through 1991, and real GDP information thereafter.

Figure 1. Real-Time Estimates and Final Estimates of the Output Gap



Note: The two panels in the top row show estimates of the output gap using real-time data and the final data available. The panels in the second row show the difference between the estimates. The panels in the third row show misperceptions along with the forecast errors for total factor productivity alongside the output gap misperceptions.

questions about the claims of Taylor (1999), Clarida, Galí, and Gertler (2000), and others who see the Federal Reserve's Federal Open Market Committee after Chairman Paul Volker's term as more disciplined in its response to inflation. They suggest, instead, that Walsh (2009, 216) may be correct in his assessment that the success of targeting inflation has more to do with the "good luck" coming from a "benign economic environment" than from improved monetary policy.

The last panel in figure 1 plots real-time output gap misperceptions against a total factor productivity forecast error series. The latter measure comes from running a rolling regression on the trend of Fernald's (2009) total factor productivity series and using it to construct a forecast for each period. The difference between actual and forecasted total factor productivity is the forecast error.[7]

The last panel also shows, especially for the Hodrick-Prescott filter, a close relationship between the total factor productivity forecast error and real-time output gap misperceptions. This suggests that supply-side shocks are key to the knowledge problem facing central bankers. Such shocks affect potential real output and thus the output gap but are notoriously hard to measure in real time. Selgin, Beckworth, and Bahadir (2015), for example, show that a key contributor to the housing boom in the early years of the 21st century was the failure of the Federal Open Market Committee to recognize and properly respond to the large productivity boom of 2002–2004. The failure to recognize this large positive supply shock can explain why monetary policy continued to ease after 2002 even though housing prices, credit growth, and nominal spending were accelerating.

Recognizing the measurement problems that supply shocks make for monetary policy, Selgin, Beckworth, and Bahadir (2015) advocate a nominal GDP target as a way to deal with this

[7] The data start in 1947:Q1, and our forecasts are based on the assumption of a slowly changing long-term trend in the data. Hence, we use a rolling sample of 92 observations, which means the first forecast is for 1970:Q1. The regression takes the natural log of Fernald's (2009) total factor productivity and regresses it on a time trend.

knowledge problem. Specifically, they note that monetary authorities can step back from worrying about the size of the output gap by focusing on anchoring the path of nominal spending. Doing so keeps total dollar spending stable while removing the need for the Federal Reserve to respond to changes in the composition of this spending from supply shocks.

Nominal GDP targeting, in other words, is a work-around for the knowledge problem facing central bankers. It is the reason Woodford (2012) endorsed it in his much publicized Jackson Hole speech and the reason Koenig (2012) is wrong to characterize the Taylor rule as a special case of nominal GDP targeting. From the knowledge problem perspective, the Taylor rule is a fundamentally different approach to monetary policy than is nominal GDP targeting. The former imposes an information requirement on central bankers that the latter does not.

Evidence from Federal Reserve's Forecasts

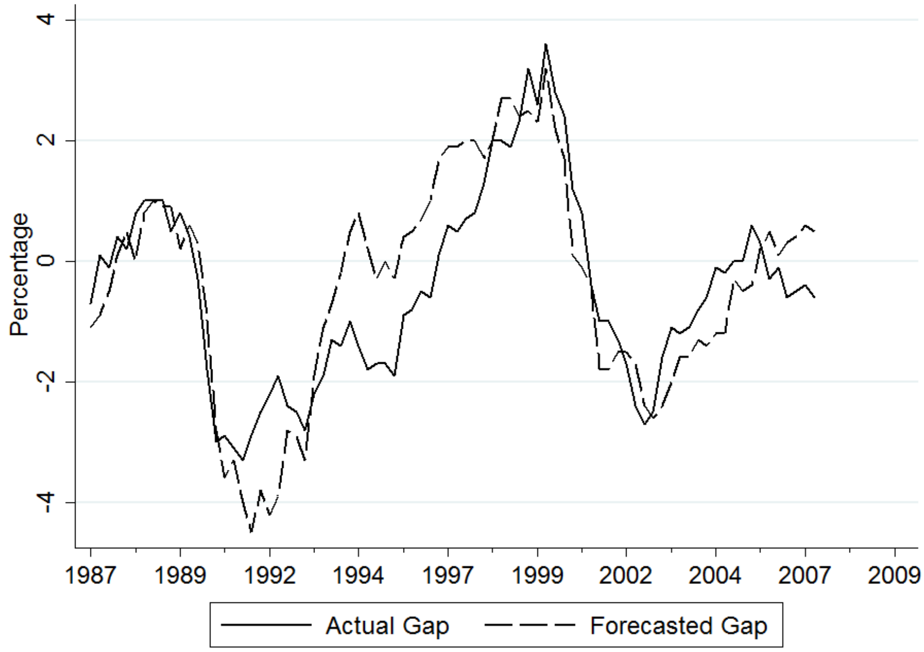
In the previous section, we argued that the use of the output gap in the conduct of policy poses a problem because of difficulties associated with estimating the output gap in real time. We showed that using standard detrending methods on the data available in real time produced estimates of the output gap that were systematically different from the actual output gap. This measurement problem also plagued the Federal Reserve. Specifically, we present evidence not only that the Federal Reserve's forecasts of the output gap systematically differ from the actual output gap but also that the Federal Reserve's forecast error follows a unit root process. In contrast, the Federal Reserve's forecast error for nominal GDP growth is stationary.

The Federal Reserve Bank of Philadelphia publishes the Greenbook forecasts of the Federal Reserve. The Federal Reserve's forecast of the output gap is available from 1987:Q1 to

2007:Q2 and is plotted in figure 2 along with the percentage deviation of real GDP from the Congressional Budget Office's estimate of real potential GDP. As shown in the figure, there are periods when the Federal Reserve's forecast differs from the ex post estimate of the output gap for prolonged periods of time. To illustrate the persistence of the differences between the Federal Reserve's forecast and the ex post estimate of the output gap, the Federal Reserve's forecast error is plotted in figure 3. As shown, the forecast error associated with the output gap appears to be relatively persistent. In fact, an augmented Dickey-Fuller test on the Federal Reserve's forecast error associated with the output gap has a test statistic of −2.41, −1.87, and −2.08 for one, two, and three lags, respectively. These test statistics are all below the 10 percent critical value necessary to reject the null hypothesis of a unit root. This is quite problematic for a monetary policy rule that puts weight on the output gap.

As noted, Selgin, Beckworth, and Bahadir (2015) advocate a nominal GDP target to circumvent the problems associated with using the output gap in policy analysis. However, to provide support for this alternative, it is important to determine whether the Federal Reserve has a better track record forecasting nominal GDP growth than it does forecasting the output gap. The Federal Reserve's forecast of nominal GDP growth and actual nominal GDP growth are shown in figure 4. An augmented Dickey-Fuller test on the corresponding forecast errors produces a test statistic of −5.84, −4.36, and −3.89 for lags of one, two, and three quarters, respectively. Each of these test statistics is sufficient to reject the null hypothesis of a unit root at the 1 percent level. It follows that the Federal Reserve's forecast errors with respect to nominal GDP growth are stationary. This, in conjunction with the estimates above of the Federal Reserve's forecast error of the output gap, suggests that the Federal Reserve does a better job forecasting nominal GDP growth than it does the output gap.

Figure 2. Output Gap—Forecasted and Actual



Note: The figure plots the forecasted gap taken from the Federal Reserve's Greenbook forecast and the actual output gap measured by the deviation of real GDP from the Congressional Budget Office's estimate of real potential GDP.

Figure 3. The Federal Reserve's Forecast Error of the Output Gap

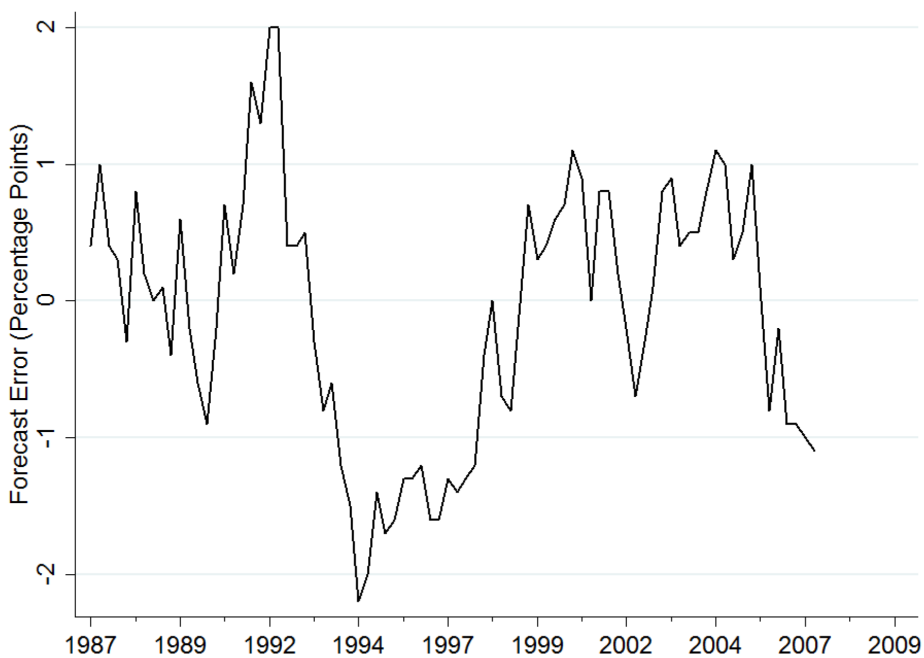
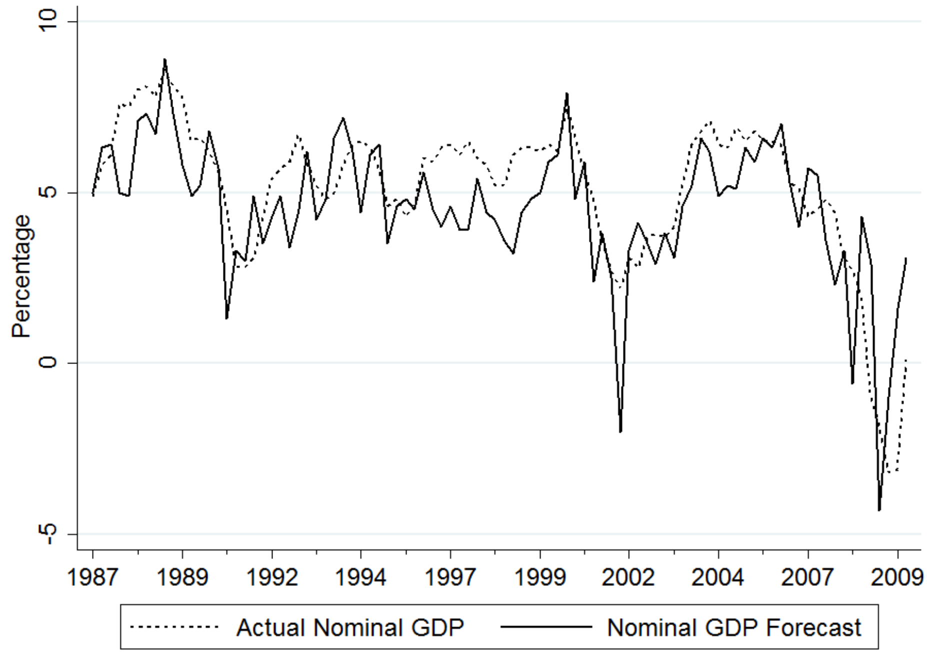


Figure 4. Nominal GDP Growth—Forecast and Actual



Note: The figure plots the Federal Reserve's Greenbook forecast of nominal GDP growth and the actual growth rate of nominal GDP. The Federal Reserve's forecast is the forecast of nominal GDP growth at the beginning of the quarter for the current quarter.

A Framework for Analysis

As noted, within the standard New Keynesian framework, the relative performance of monetary policy rules is evaluated in terms of their ability to minimize a weighted sum of the variance of inflation and the output gap. Given the fact that the Taylor rule adjusts policy to the contemporaneous inflation rate and the output gap, it is perhaps not surprising that the Taylor rule performs rather well using these criteria. Nonetheless, the assumption that the central bank is accurately able to estimate the output gap in real time is contrary to existing empirical evidence. As a result, it is important to incorporate this characteristic into the evaluation of alternative monetary policy rules.

In this section, we evaluate monetary policy rules in the following way. First, we outline a New Keynesian model in which the central bank forms an estimate of the output gap based on previous values of the actual output gap. The central bank then uses its estimate in the determination of policy. We estimate the parameters of this model using Bayesian estimation techniques. We then estimate conditional variance decompositions for the output gap.

Second, given the parameter estimates from the initial model, we generate data using two alternative models that differ only in terms of assumptions regarding the conduct of monetary policy. The first alternative is the standard New Keynesian model in which the central bank has perfect information about the output gap. The second alternative is a standard New Keynesian model in which monetary policy adjusts to deviations of nominal GDP from some arbitrary target.[8]

Finally, we use the simulations from each model to evaluate monetary policy under these different assumptions. The results then allow us to compare the performance of the nominal GDP targeting rule to the Taylor rule under different assumptions about the information set of the central bank.

The New Keynesian Model with Uncertainty Regarding the Output Gap

In this section, we present the standard New Keynesian model, modified by the assumption that the central bank does not have real-time knowledge of the output gap. Specifically, we assume that the central bank can observe the previous period's true output gap and use it to forecast the current period's output gap. The standard New Keynesian model consists of the following log-linearized equations:

$$c_t = E_t c_{t+1} - \left(\frac{1}{\sigma}\right)(r_t - E_t \pi_{t+1}) + e_t^C, \tag{2}$$

[8] This latter model is similar to the model used by Hendrickson (2012a). The assumption in this model is that monetary policy responds to deviations of nominal GDP growth from the steady state growth rate. The particular steady state growth rate, however, has no bearing on the results; hence, use of the term is arbitrary. We view this as an advantage of our analysis since it does not require stipulation of a particular target for nominal GDP and therefore applies to nominal GDP targeting generally.

$$y_t = c_t + g_t, \tag{3}$$

$$g_t = p_g g_t + e_t^g, \tag{4}$$

$$\pi_t = \beta E_t \pi_{t+1} + \kappa \tilde{y}_t + e_t^{PC}, \tag{5}$$

$$y_t^n = \theta a_t, \tag{6}$$

$$a_t = \rho_a a_{t-1} + e_t^a, \tag{7}$$

$$\tilde{y}_t = y_t - y_t^n, \tag{8}$$

where c_t is consumption, g_t is an aggregate spending/demand shock, y_t is real GDP, π_t is the rate of inflation, r_t is the nominal interest rate, $\tilde{y}_t$ is the output gap, y_t^n is the natural level of output, a_t is productivity, e_t^c is a consumption shock, e_t^{PC} is a shock to the New Keynesian Phillips curve, and σ, β, κ, θ, and ρ_a are parameters. Thus, equation (2) is the consumption Euler equation, equation (3) defines real GDP as the sum of consumption and an aggregate demand shock, equation (4) is the New Keynesian Phillips curve, equation (6) defines the natural rate of output, and equation (8) defines the output gap.

Our framework differs from the standard model in the following way. We assume that the central bank follows a Taylor rule. However, the central bank sets the nominal interest rate based on the bank's estimate of the current period's output gap:

$$r_t = \rho_r r_{t-1} + (1 - \rho_r)(\phi_\pi \pi_t + \phi_y \tilde{y}_t^{CB}) + e_t^r, \tag{9}$$

where ρ_r is an autoregressive parameter, ϕ_π is the coefficient on inflation, ϕ_y is the coefficient on the estimate of the output gap, e_t^r is a monetary policy shock, and $\tilde{y}_t^{CB}$ is the central bank's estimate of the output gap and satisfies:

$$\tilde{y}_t^{CB} = \rho_{gap} \tilde{y}_{t-1}^{CB} + (1 - \rho_{gap}) \tilde{y}_{t-1} + e_t^{gap}, \tag{10}$$

where

$$e_t^{gap} = \omega e_{t-1}^{gap} + \epsilon_t, \tag{11}$$

This assumption that the central bank's forecast error is persistent is consistent with the evidence shown in figure 3.

Equations (2)–(11) represent a system of 10 equations that solve for 10 unknowns: c_t, g_t, y_t, r_t, π_t, $\tilde{y}_t$, y_t^n, a_t, e_t^{gap}, and $\tilde{y}_t^{CB}$. We estimate the parameters of the model using Bayesian estimation techniques. The estimated parameters are then held constant in the model simulations used to evaluate the welfare properties of alternative monetary policy rules.

Estimation Details

Bayesian estimation relies on the fact that the posterior distribution of the parameters is approximately equal to the product of the likelihood of the model and the prior distribution of the parameters. This section outlines the prior distribution of the parameters and discusses how to estimate the likelihood and to characterize the posterior distribution.

One of the model parameters is calibrated. The remaining parameters are estimated. The calibrated parameter is the discount factor, β, which is set equal to 0.99, which is consistent with a discount rate of 4 percent, which is fairly standard in macroeconomic models. The prior distributions of the remaining parameters are shown in table 1. The prior mean of the parameter σ is set equal to 1, which is consistent with an assumption of log utility over consumption. We assume that this parameter follows a gamma distribution with a standard deviation of 0.5. The parameter κ measures the responsiveness of inflation to the output gap. We assume that this parameter follows a beta distribution with a mean of 0.10 and a standard deviation of 0.05. The prior mean for κ is chosen to be close to the calibration of Galí (2008), which calibrates $\kappa = 0.1275$. We assume that θ follows a gamma distribution with a mean of 1 and a standard deviation of 0.5. This parameter measures the marginal effect of technology on the natural rate of output. The prior mean is chosen to be consistent with the calibration of Galí. The parameters ϕ_π and ϕ_y are the Taylor rule coefficients. We assume that ϕ_π follows a gamma distribution with a mean of 1.5 and a standard deviation of 0.5 and that ϕ_y follows a gamma distribution with a mean of 0.125 and a standard deviation of 0.10. These parameters are chosen to be consistent with the standard Taylor rule. The parameters ρ_g, ρ_a, ρ_r, and ω represent the autoregressive parameters of the aggregate demand shock, productivity, the nominal interest rate, and the central bank's forecast error, respectively. The parameter ρ_{gap} represents the relative weight that the central bank puts on its previous estimate of the output gap compared to the actual lagged output gap. We assume each parameter follows a beta distribution with a mean of 0.5 and a standard deviation of 0.2. This represents a fairly agnostic set of priors for these parameters. Finally, we assume that each shock follows an inverse gamma distribution with a mean of 1.0 and a standard deviation of 2.0.

Table 1. Prior Distributions

Parameter	Distribution	Mean	Standard deviation
σ	Gamma	1.00	0.50
κ	Beta	0.10	0.05
ϑ	Gamma	1.00	0.50
ϕ_π	Gamma	1.50	0.50
ϕ_y	Gamma	0.125	0.05
ρ_g	Beta	0.50	0.20
ρ_a	Beta	0.50	0.20
ρ_r	Beta	0.50	0.20
ρ_{gap}	Beta	0.50	0.20
ω	Beta	0.50	0.20
SD(e^{IS})	Inverse gamma	1.00	2.00
SD(e^{PC})	Inverse gamma	1.00	2.00
SD(e^{a})	Inverse gamma	1.00	2.00
SD(e^{r})	Inverse gamma	1.00	2.00
SD(e^{g})	Inverse gamma	1.00	2.00
SD(ϵ)	Inverse gamma	1.00	2.00

The 10-equation system described above has a rational expectations solution of the form

$$S_t = AS_{t-1} + B\varepsilon_t, \quad (12)$$

$$Y_t = CS_t, \quad (13)$$

where Y_t is a vector of control variables, S_t is a vector of state variables, ϵ_t is a vector of structural shocks, and A, B, and C are parameter matrices. By defining $X_t = (Y_t' S_t')\$$, equations (12) and (13) can then be rewritten as

$$X_t = DX_{t-1} + E\varepsilon_t, \quad (14)$$

where D and E are functions of A, B, and C, and equation (14) is the state space representation of the model.

By defining $\mathcal{Y}_t$ to be a vector of observable variables, the observable variables can be written in terms of the states defined in equation (14) as

$$\mathcal{Y}_t = F + GS_t + \Xi_t, \quad (15)$$

where F is a vector of the mean of the observable variables, G is a matrix of zeros and ones relating the observables to the variables in the system, and Ξ_t is a vector of measurement errors.

By defining Γ as a vector that contains the parameters of the model. The likelihood of the model is given as

$$\mathcal{L}(\mathcal{Y}_T|\Gamma) = \sum_{t=1}^{T} \mathcal{L}\,(\mathcal{Y}_t|\mathcal{Y}_{t-1}, \Gamma),$$

where $\mathcal{L}(\mathcal{Y}_t|\mathcal{Y}_{t-1}, \Gamma)$ is the likelihood conditional on information up to time $t-1$. Given equations (14) and (15), we can use the Kalman filter to compute the likelihood function.

The posterior distribution of the parameters is characterized using the Metropolis-Hastings algorithm, which operates as follows. Given some initial vector of parameters, $\Gamma_{1,0}$, the Kalman filter can be used to estimate the likelihood. A new parameter vector is then generated according to

$$\Gamma_{1,1} = \Gamma_{1,0} + jc\varepsilon_1,$$

where c is the Choleski decomposition of the covariance matrix of Γ, j is a jump scalar, and ε_1 is a vector of elements drawn from a standard normal distribution. The Kalman filter is then used to construct the likelihood given the new parameter vector $\Gamma_{1,1}$. The Metropolis-Hastings algorithm is used to accept or reject this parameter vector. The steps are repeated for a specified number of draws, N, to determine the posterior density of the model.

Both the number of draws and the jump scalar are important for characterizing the posterior. The jump scalar should be chosen such that the acceptance rate for the Metropolis-Hastings algorithm is between 20 and 30 percent. The size of the sample also is important for convergence of the algorithm. In our estimation, we set the number of draws to 250,000, drop the first 50,000 draws, and $j = 0.55$, which produces an acceptance rate of 27.8 percent.

Results

The model is estimated using data on five variables: real GDP growth, the output gap, the Federal Reserve's forecast of the output gap, the federal funds rate, and the inflation rate. Real GDP is measured by the log difference of real GDP. The output gap is measured by the percentage difference between real GDP and the Congressional Budget Office's estimate of real potential GDP. The inflation rate is measured by the percentage change in the implicit GDP deflator from a quarter ago. The federal funds rate is the effective federal funds rate. Each variable was obtained from the St. Louis Federal Reserve's FRED (Federal Reserve Economic Data) online database. The Federal Reserve's estimate of the output gap is the forecast of the current period's output gap taken from the Federal Reserve's Greenbook forecast database. All data are quarterly and are estimated over the sample period 1987:Q3–2007:Q3. This is the sample over which the Federal Reserve's forecast of the output gap is available. The decision to use the Greenbook forecast of the output gap is so that we have a real-time estimate of the output gap to use as the central bank forecast. The estimate of the output gap based on the Congressional Budget Office's estimate of potential GDP is an ex post measure of the output gap. The estimated parameters are shown in table 2, along with the posterior mean and the 90 percent probability interval.

Table 2. Posterior Estimates

Parameter	Mean	90% probability interval
σ	5.35	3.84, 7.03
κ	0.06	0.04, 0.08
ϑ	1.36	0.50, 2.20
ϕ_π	2.03	1.90, 2.16
ϕ_y	0.96	0.79, 1.15
ρ_g	0.99	0.987, 0.998
ρ_a	0.78	0.72, 0.83
ρ_r	0.78	0.74, 0.82
ρ_{gap}	0.32	0.14, 0.49
ω	0.65	0.52, 0.78
SD(e^{IS})	2.55	2.17, 2.93
SD(e^{PC})	0.19	0.16, 0.23
SD(e^{a})	1.93	0.73, 3.32
SD(e^{r})	0.40	0.34, 0.45
SD(e^{g})	8.02	2.73, 13.40
SD(ϵ)	0.53	0.46, 0.60

Conditional Variance Decompositions

Note that our assumptions imply that the monetary policy rule followed by the central bank can be written as

$$r_t = \rho_r r_{t-1} + (1-\rho_r)(\phi_\pi \pi_t + \phi_y[\rho_{gap}\tilde{y}_{t-1}^{CB} + (1-\rho_{gap})\tilde{y}_{t-1} + e_t^{gap}] + e_t^r.$$

What this implies is that if the central bank imperfectly estimates the output gap, and a model is estimated in which the central bank has perfect knowledge about the output gap, the structural shock identified is actually a function of the central bank's forecast error.

Thus, our framework is useful because it allows us to distinguish between shocks to the central bank's estimate of the output gap from traditional monetary policy shocks that represent temporary deviations from a monetary policy rule. Conditional variance decompositions can then allow a comparison of the relative importance of the shocks. The conditional variance decompositions are given in table 3. As shown, shocks associated with consumption and technology account for most of the fluctuations in output. The monetary policy shock is also economically important as it accounts for up to 17 percent of the fluctuations in the output gap. In addition, the shock to the central bank's forecast of the output gap accounts for 13 percent of the fluctuations in the output gap. This suggests that removing the output gap from the central bank's feedback rule could potentially generate greater macroeconomic stability.

Table 3. Conditional Variance Decompositions

Variable	Periods ahead	Output gap
IS shock	1	0.40
	2	0.32
	3	0.30
	4	0.29
Phillips curve shock	1	0.03
	2	0.03
	3	0.03
	4	0.03
Technology shock	1	0.34
	2	0.37
	3	0.38
	4	0.38
Monetary policy shock	1	0.15
	2	0.17
	3	0.17
	4	0.17
Demand shock	1	0.001
	2	0.001
	3	0.001
	4	0.002
Forecast shock	1	0.07
	2	0.10
	3	0.12
	4	0.13

Evaluating Alternative Monetary Policies

As outlined above, a distinct difference between a nominal income growth target and a Taylor rule is that the latter requires knowledge of the output gap in real time. Although a target for nominal income growth would no doubt be informed by long-run averages of real GDP growth and the central bank's desired rate of inflation, the choice of a nominal income growth target need not require any knowledge of the output gap or potential GDP. Traditional analyses of the Taylor rule assume that the central bank has real-time knowledge of the output gap. If this is not true, as historical experience would seem to suggest, then the welfare properties of the Taylor rule are potentially biased. In this section, we present evidence from simulations to analyze the welfare properties under four different assumptions regarding the economy. The four frameworks are described as follows:

1. *The Taylor rule with standard New Keynesian assumptions.* This is the standard analysis in the literature. The framework consists of equations (2)–(9) under the assumption that the central bank has perfect real-time knowledge of the output gap ($\tilde{y}_t^{CB} = \tilde{y}_t$). In addition, the parameters of the Taylor rule, ϕ_π and ϕ_y, are set equal to 1.5 and 0.5, respectively, as in Taylor (1993).
2. *The Taylor rule with imperfect knowledge of the output gap.* This framework consists of equations (2)–(11) as outlined above. However, we impose Taylor rule parameters $\phi_\pi = 1.5$ and $\phi_y = 0.5$.
3. *A difference rule.* The framework consists of equations (2)–(9). However, equation (9) is modified to replace the output gap with the change in real GDP: $y_t - y_{t-1}$. This modification was first suggested by Staiger, Stock, and Watson (1997). Similarly, Orphanides and Williams (2002) show that a rule that included the change in the

unemployment rate was robust to a world in which the central bank is uncertain about the natural rate of unemployment. Since this policy is also immune to information problems associated with the output gap, this provides a Taylor rule alternative to nominal GDP targeting that is immune from our critique.

4. *A nominal income growth target.* This framework consists of equations (2)–(8), an identity that defines nominal income growth, and a nominal income target. The monetary policy rule is expressed in log deviations as

$$r_t = \rho_r r_{t-1} + (1 - \rho_r)\Omega \Delta x_t + e_t^r, \tag{16}$$

where Δx_t is nominal income growth, e_t^r is the monetary policy shock, and Ω is a parameter. Consistent with the estimates of Hendrickson (2012a) from the post-Volcker era, we assume that $\Omega = 1.78$.

Each framework is simulated by generating 100,000 observations. We keep only the last 200 observations. All the parameters and the standard deviations of the shocks used to simulate data are identical to the estimates obtained in the previous section. The only difference in the data-generating process across each different framework is the assumptions regarding monetary policy.

The standard deviations of the output gap and inflation are shown in table 4 as percentages. As shown, the standard deviation of the output gap is smallest under the standard Taylor rule with perfect information. The standard deviation of inflation is lowest under the nominal GDP targeting rule. Our argument in this paper is that the relevant comparison for analysis is between the Taylor rule under imperfect information and the nominal GDP targeting rule, since central banks do not know the output gap in real time. Under imperfect information, the standard deviations of inflation and the output gap are higher than when the central bank has perfect information, as would be expected. However, it is also true that the assumption of imperfect information implies that the standard deviations of inflation and the output gap under a Taylor rule would be higher than under a nominal GDP target. Thus, on an equal playing field, the nominal GDP target outperforms the Taylor rule.

Table 4. Standard Deviations of Output and Inflation

Model	Output gap	Inflation
Taylor rule with standard assumptions	3.57	1.15
Taylor rule with imperfect information	3.64	1.25
Nominal GDP target	3.60	0.95
Difference rule	3.76	1.26

Finally, the performance of the nominal GDP target is also favorable in comparison to the difference rule. Some have argued that a Taylor rule modified to include change in the real output rather than the output gap would be robust to the issues raised in this paper. Our results are important because they suggest that a nominal GDP target would be preferable even to the difference specification of the Taylor rule. The reason seems to be due to the fact that nominal GDP targeting, by putting equal weight on inflation and real GDP growth, effectively puts more weight on real economic activity than does the difference rule.

Conclusion

Recently, some economists have advocated nominal GDP targeting as an alternative to the Taylor rule on the grounds that (a) it allows central banks to target one variable, (b) it reduces the knowledge necessary for central bankers to conduct policy, (c) it eliminates the need for the central bank to try to control a real variable, and (d) it does not require the central bank to conduct monetary policy in accordance with real-time estimates of the output gap. We examine this claim by amending a standard New Keynesian model to assume that the central bank has imperfect information about the output gap and therefore must forecast the output gap using previous information. Forecast errors by the central bank can then potentially induce unanticipated changes in the short-term nominal interest rate, distinct from a standard monetary policy shock. Using US data, we show that forecast errors by the Federal Reserve can account for up to 13 percent of the fluctuations in the output gap. In addition, we show that simulations imply that a nominal GDP targeting rule would produce lower volatility in both inflation and the output gap in comparison with the Taylor rule under imperfect information.

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