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The Influence of the Taylor rule on US Monetary Policy*

Pelin Ilbas[†] Øistein Røisland[‡] Tommy Sveen[§]

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Abstract

We analyze the influence of the Taylor rule on US monetary policy by estimating the policy preferences of the Fed within a DSGE framework. The policy preferences are represented by a standard loss function, extended with a term that represents the degree of reluctance to letting the interest rate deviate from the Taylor rule. The empirical support for the presence of a Taylor rule term in the policy preferences is strong and robust to alternative specifications of the loss function. Analyzing the Fed's monetary policy in the period 2001 − 2006, we find no support for a decreased weight on the Taylor rule, contrary to what has been argued in the literature. The large deviations from the Taylor rule in this period are due to large, negative demand-side shocks, and represent optimal deviations for a given weight on the Taylor rule.

Keywords: optimal monetary policy, simple rules, central bank preferences

JEL Codes: E42, E52, E58, E61, E65

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1 Introduction

The Taylor rule has undoubtedly influenced the debate about monetary policy during the last 20 years. But has it also influenced actual monetary policy? According to the survey by Kahn (2012), the answer seems to be 'yes'. The transcripts from the Federal Open Market Committee (FOMC) meetings include several references to the Taylor rule. For example, at the FOMC meeting in January 31-February 1 1995, where the Greenbook suggested a 150 basis points increase of the Federal funds rate to 7 percent, FOMC member Janet Yellen expressed the following concern: "*I do not disagree with the Greenbook strategy. But the Taylor rule and other rules... call for a rate in the 5 percent range, which is where we already are. Therefore, I am not imagining another 150 basis points*".[1] Similar references to the Taylor rule can also be found from policy meetings in other central banks.[2]

However, the fact that the Taylor rule has been referred to in the policy meetings does not necessarily imply that it has had a significant influence on the decisions. One way to analyze the importance of the Taylor rule is simply to consider the correlation between the (original) Taylor rule and the actual Federal Fund's Rate. Based on this approach, Taylor (2012) argues that the Fed followed the Taylor rule quite closely until around 2003. After that, Taylor argues that the Fed abandoned the Taylor rule around 2003 and moved to a more discretionary monetary policy. Some observers see the large deviation from the Taylor rule in the period 2003 - 2006 as a policy mistake contributing to the build-up of financial imbalances and the subsequent crisis.

Instead of simply comparing the original Taylor rule with the actual interest rate, another common approach is to estimate more general specifications of the Taylor rule, e.g., by including the lagged interest rate and forward-looking terms. Clarida, Galì and Gertler (2000) showed that the Fed's policy during the Volcker-Greenspan period can be represented well by a forward-looking Taylor rule. Moreover, Bernanke (2010) replied to Taylor´s critique about the large deviations from the Taylor rule prior to the financial crisis by showing that a forward-looking Taylor rule would have implied an interest rate closer to the actual one. Similarly, Clarida (2012) argues that the Fed's policy during 2003 - 2005 was consistent with his specification of a forward-looking Taylor rule, where he uses inflation expectations derived from inflation linked bonds. However, the fact that monetary policy can be represented by an (estimated or calibrated) interest rate rule does not necessarily mean that the central bank follows a rule-based policy. Also a purely discretionary policy can be characterized by an interest rate "rule". As demonstrated by Jensen (2011), one should be careful when interpreting estimated interest rate rules, both as evidence of rule-based behavior and when investigating equilibrium determinacy.

Following a simple policy rule mechanically is both unrealistic and undesirable. This point is also recognized by proponents of rule-based policy, who recommend that one should deviate from the rule when one has information that justifies deviations. With the premise that a rule

[1] Quote taken from Kahn (2012). Kahn notes that, "[a]s it turned out at the meeting, the federal funds rate target was raised 50 basis points to 6 percent, where it stayed until July 1995 when it was cut to 5 $\frac{3}{4}$ percent."

[2] For example, the Vice-Governor at the Riksbank, Lasse Öberg, expressed on the monetary policy meeting December 14, 2010: *"With GDP growth of over 5 per cent, more or less normal resource utilisation, and inflation and inflation expectations at around 2 per cent, it feels slightly uncomfortable to have a repo rate of 1.25 per cent. A traditional Taylor rule would in the present situation result in a repo rate of 3 to 4 per cent."*

should be a guideline, but not a straitjacket, the question is when there are good reasons to deviate from the rule. Obviously, this depends on the particular shocks hitting the economy. Unless the intercept term in the Taylor rule is constantly adjusted, the Taylor rule tends to give inefficient stabilization of output and inflation when there are changes in the natural rate of interest, as the Taylor rule will then fail to close the output gap in the short run, see Woodford (2001). The inefficiency of the Taylor rule under certain shocks was also noted by the Fed staff, who, according to FOMC transcripts from November 1995, argued that the Taylor rule might be well suited for supply shocks, but a greater weight on the output gap would be better suited for demand shocks.[3] Since appropriate deviations from the Taylor rule depend on the type and size of shocks, one cannot necessarily conclude that a period of large deviations, such as in 2003 - 2005, reflect less weight on the rule in the policy decisions. An alternative explanation is that specific shocks justified larger deviations from the Taylor rule for a given weight on the rule.

An alternative to describing monetary policy in terms of a simple interest rate rule is optimal policy. Svensson (2003) argues that it is more consistent and realistic to treat the monetary policymakers as other agents in the economy, i.e., by specifying preferences (a loss function) and constraints (the model) and assuming that the policymakers act optimally subject to their information. Comparing the empirical fit of the two approaches - simple rules versus optimal policy - Ilbas (2012) finds that optimal policy describes the behavior of the Federal Reserve better than simple rules. Adolfson *et al.* (2011) find, however, that a simple rule has a slightly better empirical fit for the policy of the Swedish Riksbank.[4] In spite of the consistency argument of treating policymakers as optimizing agents, the results in the empirical literature on this issue are therefore somewhat inconclusive.

In this paper, we show that the empirical fit of optimal policy increases if one allows policymakers to pay attention to simple rules. To assess the importance placed on the Taylor rule by the Fed, and analyze if the period after 2003 represented a shift away from it, we introduce a policy preference function which includes a weight on the Taylor rule. We therefore assume that, in addition to the commonly used (*ad hoc*) loss function, the policymaker dislikes deviations of the interest rate from the Taylor rule. Our approach is inspired by Rogoff's (1985) seminal paper on the optimal degree of commitment to an intermediate target, in which he argues that *"it is not generally optimal to legally constrain the central bank to hit its intermediate target (or follow its rule) exactly"* (p.1169). Our modified loss function can either be interpreted as optimal policy with cross-checking by the Taylor rule, or alternatively as optimal deviations from a Taylor rule. This approach seems consistent with how policymakers form their interest rate decisions in practice. For example, Vice Chair Janet Yellen (2012) formulates the role of the Taylor rule in monetary policy assessments as follows: "*One approach I find helpful in judging an appropriate path for policy is based on optimal control techniques. [...]. An alternative approach that I find helpful [...] is to consult prescriptions from simple policy rules. Research suggests that these rules perform well in a variety of models and tend to be more robust than the optimal control policy derived from any single macroeconomic model.*" Given that policy-

[3] See Kahn (2012).

[4] This result hinges on the assumption of a policy shock in both the instrument rule and the targeting rule.

makers make use of both (explicit or implicit) optimal policy and simple rules, our modified loss function provides a unified approach for analyzing monetary policy decisions. A virtue of this approach is that one can analyze whether actual deviations from the Taylor rule represent optimal deviations for a given weight, or a decrease in the weight placed on the rule.

Following recent work on estimating central banks' preferences,[5] we conduct the estimations within the framework of a medium-scale DSGE model - the Smets and Wouters (2007) model - using Bayesian estimation techniques. We find that the model with the loss function that includes the original Taylor rule has a better empirical fit than the model with the standard loss function. Our result therefore confirms the indirect evidence in Kahn (2012) on the influence of the Taylor rule on the FOMC's policy decisions. An alternative (and less favorable) interpretation of the results is that the estimated weight on the Taylor rule reflects model misspecification rather than policy preferences, as the original Taylor rule is known to describe the Fed's behavior reasonably well. We address this issue by considering an OLS-estimated Taylor rule, and find that neither the weight on the Taylor rule nor the empirical fit improves, which provides evidence in favor of the policy preferences interpretation. Moreover, we find that the weight on the Taylor rule did not decrease in the period after 2003, contrary to what Taylor (2012) argues. When decomposing the various shocks hitting the US economy, we find that in the period 2001 - 2006, large negative demand-side shocks were dominating. As noted above, this is the type of disturbances that should make the policymaker deviate from the Taylor rule. Indeed, the optimal policy response to these shocks implied an even lower interest rate than the actual Fed Funds Rate. We thus find that in the period 2001 - 2006 the Fed conducted a *more contractionary* policy than what would be implied by their historical reaction pattern.

The paper is organized as follows: Section 2 presents the theoretical framework. Section 3 explains the estimation procedure. Section 4 discusses the empirical results, including an analysis of the robustness of the results, and assessment of Fed's monetary policy prior to the financial crisis based on our estimated model. Section 5 concludes.

2 Theoretical Framework

In this section, we set out the model used in this paper to represent the US economy, i.e. the linearized Smets and Wouters (2007) model with minor modifications, followed by the assumptions about the behavior of monetary policy. Unlike the original Smets and Wouters (2007) approach, where monetary policy is represented by a Taylor type of rule, we will assume that the central bank minimizes an intertemporal quadratic loss function under commitment where additional weight is assigned to deviations from a standard, predescribed Taylor rule as in a companion paper (Ilbas, Røisland and Sveen, 2012).

2.1 The Smets and Wouters model for the US economy

The linearized model is set out below, where we use the same notation as in the original Smets and Wouters (2007) version. The linearization is performed around the steady state balanced

[5] Ilbas (2010 and 2012), Bache et al. (2008) and Adolfson et al. (2011).

growth path and the steady state values are denoted by a star.

The household sector supplies differentiated labor, which is sold by an intermediate labor union to perfectly competitive labor packers, who in turn resell labor to intermediate goods producers. The goods markets consist of intermediate goods producers that operate under monopolistic competition and final goods producers that are perfectly competitive. The producers of intermediate goods sell these to the final goods firms who package them into one final good which is resold to the households.

The following consumption Euler equation is derived from the maximization of the households' non-separable utility function with two arguments, i.e., consumption and leisure:

$$c_t = c_1 c_{t-1} + (1-c_1)E_t c_{t+1} + c_2(l_t - E_t l_{t+1}) - c_3(r_t - E_t \pi_{t+1} + \varepsilon_t^b) \tag{1}$$

where

$$c_1 = \frac{\lambda/\gamma}{1+\lambda/\gamma}, c_2 = \frac{(\sigma_c - 1)(W_*^h L_*/C_*)}{\sigma_c(1+\lambda/\gamma)} \text{ and } c_3 = \frac{1-\lambda/\gamma}{\sigma_c(1+\lambda/\gamma)}$$

with γ the steady state growth rate and σ_c the intertemporal elasticity of substitution. Consumption c_t is expressed with respect to an external, time-varying, habit variable, leading to persistence in the consumption equation where λ is the nonzero habit parameter. Consumption is also affected by hours worked l_t, and, more precisely, is decreasing in the expected increase in hours worked $(l_t - E_t l_{t+1})$, and by the ex ante real interest rate $(r_t - E_t \pi_{t+1})$, where r_t is the period t nominal interest rate and π_t is the inflation rate. The disturbance term ε_t^b, which is an AR(1) process with i.i.d. normal error term ($\varepsilon_t^b = \rho_b \varepsilon_{t-1}^b + \eta_t^b$), captures the difference between the interest rate and the required return on assets owned by households. This shock is also meant to capture changes in the cost of capital, and resembles the shock to the risk premium of Bernanke, Gertler and Gilchrist (1999).

Wage setting by the intermediate labor union implies a standard equation for the real wage w:

$$w_t = w_1 w_{t-1} + (1-w_1)(E_t w_{t+1} + E_t \pi_{t+1}) - w_2 \pi_t + w_3 \pi_{t-1} - w_4 \mu_t^w + \varepsilon_t^w + \varepsilon_t^{lab} \tag{2}$$

where

$$\begin{aligned} w_1 &= \frac{1}{1+\beta\gamma^{1-\sigma_c}}, w_2 = \frac{1+\beta\gamma^{1-\sigma_c}\iota_w}{1+\beta\gamma^{1-\sigma_c}}, w_3 = \frac{\iota_w}{1+\beta\gamma^{1-\sigma_c}} \\ \text{and } w_4 &= \frac{(1-\beta\gamma^{1-\sigma_c}\xi_w)(1-\xi_w)}{(1+\beta\gamma^{1-\sigma_c})\xi_w((\phi_w - 1)\varepsilon_w + 1)} \end{aligned}$$

with β the households' discount factor and ξ_w the Calvo-probability that nominal wages cannot be re-optimized in a particular period, i.e., the degree of wage stickiness. Wages that cannot be re-optimized in a particular period are partially indexed, with a degree of ι_w, to the past inflation rate, leading to the dependence of wages on previous period's inflation rate. The symbol ε_w is the curvature of the Kimball labor market aggregator and $(\phi_w - 1)$ the constant mark-up in the labor market. The wage mark-up, i.e., the difference between the real wage and the marginal rate of substitution between consumption and labor, is represented as follows:

$$\mu_t^w = w_t - mrs_t = w_t - (\sigma_l l_t + \frac{1}{1-\lambda}(c_t - \lambda c_{t-1})) \tag{3}$$

with σ_l the elasticity of labor supply with respect to the real wage. Following Smets and Wouters (2003), we include a shock to the labor supply, $\varepsilon_t^{lab} = \rho_{lab}\varepsilon_{t-1}^{lab} + \eta_t^{lab}$ (with i.i.d. normal error η_t^{lab}), which, unlike the wage mark-up shock $\varepsilon_t^w = \rho_w \varepsilon_{t-1}^w + \eta_t^w - \mu_w \eta_{t-1}^w$ (with η_t^w an i.i.d. normal error), affects wages in both the sticky price and the flexible price versions of the economy. As discussed in the next section, we introduce an observable for the output gap that is in line with the historical output gap estimates considered by the Fed in monetary policy decisions. A consequence of introducing the output gap observable is that it allows us to separately identify these two shocks in a way that is consistent with the Fed's view of capacity utilization.[6]

The utilization rate of capital can be increased subject to capital utilization costs. Households rent capital services out to firms at a rental price. The investment Euler equation is represented as follows:

$$i_t = i_1 i_{t-1} + (1 - i_1)E_t i_{t+1} + i_2 q_t + \varepsilon_t^i \tag{4}$$

where

$$i_1 = \frac{1}{1 + \beta\gamma^{1-\sigma_c}}, i_2 = \frac{1}{(1 + \beta\gamma^{1-\sigma_c})\gamma^2\varphi}$$

with φ the elasticity of the capital adjustment cost function in the steady state, and $\varepsilon_t^i = \rho_i \varepsilon_{t-1}^i + \eta_t^i$ an AR(1) investment specific technology shock with i.i.d. error term. The real value of capital (q_t) is given by:

$$q_t = q_1 E_t q_{t+1} + (1 - q_1)E_t r_{t+1}^k - (r_t - E_t \pi_{t+1} + \varepsilon_t^b) \tag{5}$$

where

$$q_1 = \beta\gamma^{-\sigma_c}(1 - \delta) = \frac{(1 - \delta)}{R_*^k + (1 - \delta)}$$

with δ the capital depreciation rate, and r_t^k the rental rate of capital with steady state value R_*^k. Capital services used in current production (k_t^s) depend on capital installed in the previous period since newly installed capital becomes effective with a lag of one period:

$$k_t^s = k_{t-1} + z_t \tag{6}$$

with z_t the capital utilization rate, which depends positively on r_t^k:

$$z_t = z_1 r_t^k \tag{7}$$

where

$$z_1 = \frac{1 - \psi}{\psi}$$

[6] The distinction between both shocks is shown to be relevant by Chari, Kehoe and McGrattan (2007), and has important policy implications since the labor supply shock will affect the level of potential output, while the wage mark-up shock will not. Galí, Smets and Wouters (2012) improve the identification of the two shocks by reinterpreting hours worked as the fraction of the household members that are working, and using the unemployment rate as an observable variable. Justiniano, Primiceri and Tambalotti (2010) assume the labor supply shock to be autocorrelated, while the wage mark-up shock is assumed to be white noise. They argue that this difference in the stochastic structure is sufficient to separately identify both shocks. Galí, Gertler and López-Salido (2007) use a third-order polynomial to pick up the preference shifter (the labor supply "shock").

with ψ normalized between zero and one, a positive function of the elasticity of the capital utilization adjustment cost function. The capital accumulation equation is written as follows:

$$k_t = k_1 k_{t-1} + (1 - k_1) i_t + k_2 \varepsilon_t^i \tag{8}$$

where

$$k_1 = \frac{(1-\delta)}{\gamma} \text{ and } k_2 = (1 - (1-\delta)/\gamma)(1 + \beta\gamma^{1-\sigma_c})\gamma^2\varphi$$

The monopolistically competitive intermediate goods producers set their prices in line with Calvo (1983), which leads to the following New-Keynesian Phillips curve:

$$\pi_t = \pi_1 \pi_{t-1} + (1 - \pi_1) E_t \pi_{t+1} - \pi_2 \mu_t^p + \varepsilon_t^p \tag{9}$$

where

$$\pi_1 = \frac{\beta\gamma^{1-\sigma_c}\iota_p}{1 + \beta\gamma^{1-\sigma_c}\iota_p} \text{ and } \pi_2 = \frac{(1 - \beta\gamma^{1-\sigma_c}\xi_p)(1 - \xi_p)}{(1 + \beta\gamma^{1-\sigma_c}\iota_p)\xi_p((\phi_p - 1)\varepsilon_p + 1)}$$

and ι_p is the indexation parameter, ξ_p the degree of price stickiness in the goods market, ε_p the curvature of the Kimball aggregator and $(\phi_p - 1)$ the constant mark-up in the goods market. μ_t^p is the price mark-up, i.e., the difference between the marginal product of labor and the real wage:

$$\mu_t^p = mpl_t - w_t = \alpha(k_t^s - l_t) + \varepsilon_t^a - w_t \tag{10}$$

The price mark-up shock follows an ARMA(1,1) process: $\varepsilon_t^p = \rho_p \varepsilon_{t-1}^p + \eta_t^p - \mu_p \eta_{t-1}^p$ where η_t^p is an i.i.d. normal error term. $\varepsilon_t^a = \rho_a \varepsilon_{t-1}^a + \eta_t^a$ is the total factor productivity with an i.i.d. normal error term. The firms' cost minimization condition results into the following relation between the rental rate of capital, the capital-labor ratio and the real wage:

$$r_t^k = -(k_t - l_t) + w_t \tag{11}$$

Equilibrium in the goods market is represented as follows:

$$\begin{aligned} y_t &= c_y c_t + i_y i_t + z_y z_t + g_y \varepsilon_t^g \\ &= \phi_p(\alpha k_t^s + (1-\alpha) l_t + \varepsilon_t^a) \end{aligned} \tag{12}$$

where y_t represents aggregate output, $z_y = R_*^k k_y$, $c_y = 1 - g_y - i_y$ the steady state share of consumption in output, $i_y = (\gamma - 1 + \delta) k_y$ the steady state share of investment in output, k_y the steady state share of capital in output and g_y the ratio of exogenous spending over output. Exogenous spending is assumed to follow an AR(1) process, including an i.i.d. total factor productivity shock: $\varepsilon_t^g = \rho_g \varepsilon_{t-1}^g + \eta_t^g + \rho_{ga}\eta_t^a$. ϕ_p equals one plus the share of fixed costs in production and α is the capital share in production.

2.2 Output gap measure

The definition of the flexible price equilibrium allows us to derive a measure for the output gap in terms of deviations of output from its flex-price level. Some policymakers, however, have been critical about the DSGE-based measures of potential output. For example, Mishkin

(2007)[7] refers to DSGE based measures of the output gap as being controversial, more model-dependent and quite different for particular periods than the more conventional measures based on aggregate and production function approaches. Given the uncertainty surrounding estimates of potential output, a number of alternative methods and a lot of judgment are involved in the construction of the output gap at the Fed (Mishkin, 2007).[8] Given the implications of the output gap estimates on policy decisions, it is crucial to have a reasonable approximation of the relevant path of potential output considered by the Fed throughout our estimation sample in order to be able to provide a realistic description of the policy process and the role played by the Taylor rule therein. We therefore consider a measure of the output gap that is consistent with policymakers' perspectives on capacity utilization, and introduce an observable that is based on the HP-filter.[9] While it might arguably be more reasonable to use the Greenbook estimate instead of the HP-based gap to capture the policymakers' true assessments, both series are closely related while the Greenbook series is not complete. However, we investigate the robustness of the estimated model to the use of the historical Greenbook estimates (and the CBO-based gap) in section 4.3.

2.3 Monetary Policy

This section discusses the assumptions made about monetary policy in the estimation process. We will describe monetary policy as an intertemporal quadratic optimization problem, where, in addition to the standard target variables, deviations of the interest rate from a predescribed Taylor rule are penalized . We first set out the framework for the case of a standard loss function for monetary policy, followed by a discussion on the importance of simple rules in practice and how we incorporate the latter into the intertemporal optimization problem of the central bank.

2.3.1 Optimal Monetary Policy

Monetary policy is assumed to minimize the following intertemporal quadratic loss function L_{t+i}:

$$E_t \sum_{i=0}^{\infty} \zeta^i [Y'_{t+i} W Y_{t+i}], \qquad 0 < \zeta < 1 \tag{13}$$

where ζ is the monetary policy discount factor. The vector Y_t represents the variables in the model, including the monetary policy instrument, i.e., the interest rate r_t. W is a time-invariant symmetric, positive semi-definite matrix of policy weights, reflecting the preferences of the central bank. By assigning monetary policy a loss function of the type (13), we implicitly assume that US monetary policy can be approximated by optimal behavior. Although this might not be a reasonable assumption for the early pre-Volcker years, it is more realistic to describe the period over 1990:1-2007:4, i.e., the sample period considered in the estimation

[7] See also Bean (2005).

[8] Mishkin (2007) argues that traditionally, relatively more weight has been put on the production function approach.

[9] Having an additional observable allows us to introduce the labor supply shock, as discussed above, and to identify it separately from the wage mark-up shock.

process in the next section, as being consistent with implicit inflation targeting. The reason is that monetary policy actions during a large part of the sample spans the Greenspan era, which is characterized by an environment of low and stable inflation, and can be considered as resulting from optimizing behavior by monetary policy makers in the context of an (implicit) inflation targeting regime which became widespread in theory and practice from the 1990s. Moreover, Ilbas (2012) reports empirical evidence in favor of policy optimality during the Great Moderation period (i.e., approximately over 1984:1-2007:2). It is important to also note that we assume that the monetary policy decision making process is described as one of an individual, hence possible outcomes resulting from majority vote by the FOMC members are excluded in our context. Although this can be criticized due to its lack of realism, we rely on Blinder (2004, chapter 2) to describe the FOMC to be an "autocratically collegial committee" during the period under Greenspan, who dominated the committee's decisions over monetary policy during his term. Hence, we do not consider it unrealistic to assume that monetary policy can be described as the outcome of the decision process of an individual chairman, although we keep in mind that this assumption might hold less for the latter part of our sample, given that decision making by committee seems to play a bigger role under Bernanke.

We consider the following, rather standard, formulation for the one-period ad hoc loss function for (13):

$$L_t = {\pi_t}^2 + q_y(y_t - y_t^p)^2 + q_{rd}(r_t - r_{t-1})^2 \tag{14}$$

where monetary policy is concerned about stabilizing inflation around the (steady state) target rate, whose weight in the loss function is normalized to one, output around its potential (model-dependent) level[10] and the interest rate around its previous level. Equation (14) is a case that can be referred to as a standard flexible inflation targeting regime.

The intertemporal loss function (13), with the period loss given by (14), is minimized by the policy maker under the assumption of commitment. The optimization is performed subject to the structural equations of the economy (1) - (12) augmented by their flexible price versions. The structural model equations are represented as:

$$Ax_t = BE_t x_{t+1} + Fx_{t-1} + Gr_t + De_t, \qquad e_t \sim iid[0, \Sigma_{ee}] \tag{15}$$

with e_t an $n \times 1$ vector of stochastic innovations to the variables in x_t, with mean zero and variance-covariance matrix Σ_{ee}.

We follow the routine outlined in Dennis (2007) to perform the optimization and partition the matrix of weights W in (13) as follows:

$$E_t \sum_{i=0}^{\infty} \zeta^i [x'_{t+i} Q x_{t+i} + r'_{t+i} \Theta r_{t+i}], \qquad 0 < \zeta < 1 \tag{16}$$

where the loss function is re-written in terms of the variables x_t and r_t. The following system represents the Euler equations derived from the optimization problem of the central bank:

$$A1^* \Upsilon_t = B1^* E_t \Upsilon_{t+1} + C1^* \Upsilon_{t-1} + D1^* e_t \tag{17}$$

[10] The model-dependent level of output is defined as the output level that one obtains under the assumption of nominal wage and price flexibility and in absence of price and wage mark-up shocks.

with:

$$
\begin{aligned}
A1^* &= \begin{bmatrix} Q & 0 & A' \\ 0 & \Theta & -G' \\ A & -G & 0 \end{bmatrix} \qquad B1^* = \begin{bmatrix} 0 & 0 & \zeta F' \\ 0 & 0 & 0 \\ B & 0 & 0 \end{bmatrix} \\
C1^* &= \begin{bmatrix} 0 & 0 & \frac{1}{\zeta}B' \\ 0 & 0 & 0 \\ F & 0 & 0 \end{bmatrix} \qquad D1^* = \begin{bmatrix} 0 \\ 0 \\ D \end{bmatrix} \\
\text{and } \Upsilon_t &= \begin{bmatrix} x_t \\ r_t \\ \omega_t \end{bmatrix} = \begin{bmatrix} Y_t \\ \omega_t \end{bmatrix}
\end{aligned} \tag{18}
$$

The final vector ω_t in Υ_t contains the Lagrange multipliers. The matrices $A1^*, B1^*, C1^*$ have a dimension of size $(2n+p) \times (2n+p)$. The system in the form of (17) is estimated in the next section with Bayesian inference methods, after adjusting the loss function (14) to include a term that penalizes deviations of (optimal) policy from a predescribed Taylor rule.

2.3.2 Simple Rules

The alternative to representing monetary policy as the outcome of an optimization process as described in the previous subsection, is to assume that monetary policy follows an instrument rule where the policy instrument, i.e. r_t, is linked to a set of variables:

$$r_t = f x_t \tag{19}$$

where f is a vector that contains the coefficients in the instrument rule. These coefficients can be either obtained through the minimization of a loss function of the type (13) subject to the structural model of the economy, leading to an optimal simple rule, or through imposing restrictions on f that are not guided by any optimization routine. The rule obtained through the latter procedure can be referred to as a simple rule, with the most well-known example being the rule proposed by Taylor (1993), i.e.:

$$r_t^T = 1.5\pi_t + 0.5(y_t - y_t^p) \tag{20}$$

Although an optimal simple rule is more appropriate within the context of a single reference model since it will lead to lower unconditional losses, a simple rule is less model-dependent and hence more likely to guard against model uncertainty when policy makers do not have a strong belief in a particular benchmark model (see Taylor and Williams, 2010 and Ilbas, Røisland and Sveen, 2012). The classical Taylor rule and alternative versions based on the latter, i.e., Taylor type of rules, are popular among policy makers as well as academic researchers not only because of their model-independence feature. Taylor type of rules are intuitively appealing and used by policy makers in practice as a guide for defining the stance of monetary policy and communicating policy decisions to the public.

Given the indirect evidence in favor of the influential role of the Taylor rule as a guide for policy makers in the US and other countries, we will consider an explicit role for the Taylor rule in the optimization problem of the central bank and modify the loss function (14) accordingly. This is described next.

2.3.3 Combined Approach

Although the optimal monetary policy approach ensures the best outcome in terms of minimized unconditional loss, its virtue is highly dependent and conditional on the assumption that the policy maker is certain about the structural representation of the model economy. This implies that optimal policy is not an appropriate tool to analyse monetary policy when the central bank believes that it faces too much uncertainty to rely on one benchmark (core) structural model. In the face of such uncertainty, the central bank can insure against bad outcomes within the context of a single reference model by taking into account the policy recommendations from a Taylor rule[11]. Ilbas, Røisland and Sveen (2012) show that by placing some weight on the Taylor rule in the loss function of monetary policy, disastrous outcomes can be prevented and more robust policy can be achieved in the face of model uncertainty. Moreover, given the practical relevance of the Taylor rule in FOMC decisions, as documented in Kahn (2012), combining both approaches will allow us to provide empirical evidence on the extent to which US policy makers have relied on the Taylor rule within the context of an implicit inflation targeting regime over the last two decades. We therefore leave aside the reasons behind a possible weight on the Taylor rule, as they are discussed in more detail in Ilbas, Røisland and Sveen (2012) and Kahn (2012).

As in Ilbas, Røsiland and Sveen (2012), we modify the loss function (14) in order to include the deviation of the interest rate from a predescribed Taylor rule[12]:

$$L_t^* = (1 - q_T)L_t + q_T(r_t - r_t^T)^2 \tag{21}$$

where q_T reflects the importance assigned to the Taylor rule in minimizing the loss function. Note that the modified loss function can alternatively be regarded as a weighted average of the standard loss function (14) and the deviation of the interest rate from the standard Taylor rule, where the weight assigned to the Taylor rule reflects the degree of importance the policy makers attach to the recommendations of the latter in spite of operating in a context of optimal monetary policy. Alternatively, the choice of q_T reflects the degree of confidence the policy makers have in the reference model; a higher weight on the deviations from the Taylor rule can be regarded as a lower confidence in the reference model being a reasonable representation of the economy (Ilbas, Røisland and Sveen, 2012).

3 Estimation: Data and Methodology

We use a quarterly dataset containing following eight observables: log difference of the real GDP, log difference of real consumption, log difference of real investment, log difference of real wage, log of hours worked, log difference of the GDP deflator, the federal funds rate and the output gap measured as deviation of the real GDP from its HP-trend.

[11] The analysis of optimal monetary policy making in the presence of multiple, competing, models is beyond the scope of this paper. For this subject, see Ilbas, Røisland and Sveen (2012) and the references therein.

[12] In section 4.3.3, we replace the original (1993) Taylor rule coefficients in (20) by the (1999) Taylor rule coefficients and by their OLS-estimated counterparts, respectively, in order to investigate the robustness of the results.

Appendix I contains the details regarding the dataset. The estimation sample ranges over the period 1990:1-2007:4. The reason for not starting the sample at a date prior to 1990:1 is that it would not be a realistic assumption to allow policy makers to consider the Taylor rule a long time before the rule was proposed by Taylor in 1993.[13] We consider a training sample of 20 quarters (i.e., 5 years) to initialize the estimations.[14] The reason for limiting the estimation period to 2007:4 is due to the distortionary effects of the binding zero lower bound and the crisis period on the estimates of some of the structural parameters, such as the wage rigidities[15].

The structural equations are accompanied by eight structural shocks (ε_t^b, ε_t^w, ε_t^{lab}, ε_t^i, ε_t^p, ε_t^a, ε_t^g, ε_t^m) with the latter shock being an AR(1) shock to the first order condition of the policy instrument r_t in (17), i.e., $\varepsilon_t^m = \rho_m \varepsilon_{t-1}^m + \eta_t^m$, with $\sigma_m > 0$, which is introduced to play the role of a monetary policy shock, as in Dennis (2006) and Ilbas (2012), given that such shock would otherwise be absent in our context of optimal monetary policy[16].

The system (17) is estimated with Bayesian estimation methods, yielding estimates of the policy preference parameters in the loss function (21) along with the structural parameters. The observed quarterly growth rates in the real GDP, potential GDP, real consumption, real investment and real wages are split into a common trend growth, $\bar{\gamma} = (\gamma - 1)100$, and a cycle growth. Hours worked in the steady state is normalized to zero. The quarterly steady state inflation rate $\bar{\pi} = (\Pi_* - 1)100$ serves the role of the inflation target, implying that monetary policy's objective is to stabilize inflation around its sample mean, as in Ilbas (2010) and (2012). Finally, we estimate $\bar{r} = (\frac{\gamma^{\sigma_c}\Pi_*}{\beta} - 1)100$, which is the steady state nominal interest rate.
Following Justiniano, Primiceri and Tambalotti (2011), de Antonio Liedo (2011) and Galí, Smets and Wouters (2012), we introduce an AR(1) measurement error to the measurement equation of the wages, since the latter allows us to pin down the estimated volatility of the wage mark-up shock.

We initially maximize the posterior distribution around the mode, and use the Metropolis-Hastings algorithm to draw from the posterior distribution in order to approximate the moments of the distribution and calculate the modified harmonic mean.[17] We refer to Appendix II for assumptions regarding the prior distributions of the parameters.

4 Results

This section discusses the results based on the estimation of the system (17), where the results obtained for the case of a positive weight on the Taylor rule in the loss function is compared to the case where this weight is imposed to be zero, i.e., the standard inflation targeting case.

[13] However, by starting our sample period in 1990, we take into account the fact that the Taylor rule was already known for a short period in academic circles and among policy makers prior to the Carnegie Rochester Conference in 1993.

[14] As shown in Ilbas (2010), parameter estimation results under commitment can be considered to be in line with those under the timeless perspective when a training sample is used that is sufficiently long and that serves as a transition period after the initial period of the optimization, regardless of the initial values (which in this case are set to zero) assigned to the Lagrange multipliers.

[15] see Galí (2011) and Galí, Smets and Wouters (2012) for more details.

[16] We assume serial correlation in this shock in order to remain consistent with the other structural shocks in the model.

[17] For estimation purposes we rely on *dynare*, which can be downloaded from the website *www.dynare.org.*

This comparison will allow us to quantify the importance of the Taylor rule in optimal policy decisions. We further check for the robustness of our findings to alternative loss function specifications and analyze the behavior of the Fed during the post-2001 recession period within our proposed framework.

4.1 Parameter Estimates

The system (17), where the loss function specification (21) is used to represent optimal monetary policy, is estimated with the Metropolis-Hastings sampling algorithm based on $600,000$ draws.[18] Table 1 reports the results for the posterior mode and the posterior distribution (the posterior mean and the 90% lower and upper bounds) of the estimated parameters.[19] The estimated posterior mean values for the structural parameters are generally in line with those reported by Smets and Wouters (2007) and Ilbas (2012) for the corresponding parameters.[20]

[Insert Table 1]

Also regarding the estimates of the shocks, we find similar values for the shocks processes when compared to the estimated values for corresponding shocks obtained by Smets and Wouters (2007) and Ilbas (2012). An interesting finding based on the estimates and the posterior distributions is that both the labor supply and the wage mark-up shocks are well-identified with relatively tight posterior distributions.

Regarding the estimates of the policy parameters, it turns out that, as in the case of the other structural parameters, the data is quite informative regarding the inflation target and the policy preference parameters. We find an annualized inflation target rate of 2.16%, which is slightly lower than the prior value but in line with the findings of Ilbas (2012) and Dennis (2004). The stabilization of the interest rate around the Taylor rule receives a weight of 0.42 in the loss function, which makes the Taylor rule the most important target after inflation stabilization according to the estimates reported in Table 1, followed by interest rate smoothing and the output gap with total weights of 0.39 and 0.15[21], respectively.[22] The estimated value for q_T suggests that the Taylor rule has been an important input in monetary policy decisions when the latter is represented as an optimal inflation targeting problem. This result also confirms the indirect evidence from the FOMC transcripts, as reported in Kahn (2012), on the importance of the Taylor rule for monetary policy makers in making their policy related decisions. In the

[18] The first 20% of the draws are discarded and a step size of 0.2 is used. We use the Brooks and Gelman (1998) univariate diagnostics for each parameter and the multivariate diagnostics for all parameters to assess convergence.

[19] Figures of prior and posterior distributions of all parameters are available on request.

[20] With the exception of the habit persistence and Calvo wage stickiness parameters that are estimated to be slightly lower than the values reported by these previous studies. The Calvo price stickiness parameter, the elasticity of labor supply with respect to the real wage and the price indexation parameters on the other hand are estimated to be somewhat higher than in Smets and Wouters (2007) and Ilbas (2012).

[21] Note that these total weights are obtained by multiplying the estimated values reported in the table by $(1 - q_T)$.

[22] The estimated values for interest rate smoothing and the output gap are in line with those reported in the literature on estimated loss functions in forward-looking models (e.g. Ozlale, 2003; Castelnuovo, 2006; Dennis 2004,2006; Salemi, 2006 and Givens and Salemi, 2008). See Ilbas (2010) and the references therein for an elaborated discussion.

next section, we assess the empirical importance of the presence of the Taylor rule in the loss function of monetary policy.

4.2 How Strong is the Empirical Evidence in Favor of the Taylor Rule in the Loss Function?

Although the estimation results discussed in the previous section suggest that there is a high degree of importance attached to the Taylor rule in the loss function of monetary policy, it is important to compare the fit of the model to the case in which the Taylor rule is absent from the loss function[23]. In addition to comparing the fit of the models, we also examine which version is better in capturing the volatilities in the target variables.

We re-estimate the system (17), where monetary policy is assumed to operate under a standard flexible inflation targeting regime with loss function (14). Table 2 shows the estimation results obtained with the same procedure used in the previous section.

[Insert Table 2]

Before we compare the empirical fit of the two alternative standard loss function specifications, i.e., (14) and (21), we discuss how the estimates of certain parameters change when monetary policy is assumed to minimize a standard loss function and hence does not place any weight on the Taylor rule. Similar to the findings in Ilbas (2012), there seems to be a higher degree of habit persistence when a standard loss function is assumed. Overall, the estimated standard errors remain very similar to the previous case. Turning to the policy parameters, the inflation target is estimated to be slightly higher, i.e., 2.4% annualized, compared to 2.16% obtained in the previous section. The estimates of the policy preference parameters, i.e., the preference for output gap stabilization and interest rate smoothing, remain similar to the values obtained previously; interest rate smoothing receives the highest weight after inflation, followed by the output gap.

Given that both cases discussed in Tables 1 and 2 differ only in their specification of the loss function, in particular whether or not the Taylor rule is included, a comparison of the empirical fit of the alternative versions will give us an indication of how much the data supports the view that policy makers have assigned a non-zero weight on the Taylor rule in their decision making process.

[Insert Table 3]

[23] We also compare the fit of the model to the case where monetary policy is assumed to follow a simple rule rather than being optimal, i.e., we test for the optimality assumption of monetary policy in general. A simple rule of the Taylor type with only a few arguments typically does a worse job at fitting data. Therefore, a more generalized Taylor rule, i.e., the one applied by Smets and Wouters (2007), with lagged terms and more arguments is used for this comparison exercise. We find that the optimality assumption is more appropriate and favored by the data than the alternative of a non-optimal, generalized, Taylor rule. This is in line with the findings of Ilbas (2012), where the optimality assumption is tested over the Volcker-Greenspan sample, which for a large part includes the sample period considered in this paper. Givens (2012) estimates a simplified version of the US economy assuming optimal policy over the Volcker-Greenspan-Bernanke period and also finds empirical evidence for the case of optimal (discretionary) policy. The sample periods considered in both papers largely overlap the period considered in this paper. Due to spatial limitations, we will focus only on the case of optimal policy with a standard versus extended loss function here.

The first row in table 3 shows a comparison of the empirical fit of the alternative loss function specifications based on the marginal likelihood measures. It appears that the data slightly prefers the loss function specification that attaches positive weight on the Taylor rule, with a marginal likelihood of -402.52 against -413.41 in the case where this weight is imposed to be zero. The drawback of this comparison is that the value of the marginal likelihood is affected by the choice of priors, which can bias the model selection process (see, e.g., Sims, 2003 and Koop, 2004). Therefore, we use the approach proposed by Sims (2003) to cancel out the prior effects on the values of the marginal likelihood for each alternative model specification. The second row of Table 3 reports, for each model specification, the one-step-ahead predictive likelihood[24], i.e., the difference between the marginal likelihood computed for the full sample 1985:1-2007:4 (hence the training sample and the estimation sample combined) and the marginal likelihood obtained with the training sample, i.e., 1985:1-1989:4. Hence, the alternative specifications can now be compared against the standard of what additional evidence is provided by the estimation sample relative to the training sample (Sims, 2003). This comparison confirms the evidence in favor of a positive weight on the Taylor rule in the loss function.

Table 4 provides an additional comparison exercise based on the implied volatilities of the target variables[25] in each version of the model and the volatilities obtained with actual data. The loss function specification with positive weight on the Taylor rule performs better than the alternative case of standard inflation targeting in matching the actual volatilities of the target variables.

[Insert Table 4]

4.3 Robustness

This section discusses the robustness of our specification of the loss function (21) to the alternative specifications where the interest rate smoothing term and the Taylor rule term are, respectively, replaced by the interest rate level. We also look at the effects of replacing the original (1993) Taylor rule by the (1999) Taylor rule, where the coefficient on the output gap is set to be 1.0 instead of 0.5. In a final robustness exercise, we replace the output gap based on the HP-filter as observable in the estimation by alternative output gap measures.

4.3.1 Replacing the interest rate smoothing term by the interest rate level

In a number of alternative variations to the standard loss function, an interest rate variability objective is included in order to take into account the constraints related to the zero lower bound (see, e.g., Woodford, 1999). Ilbas (2012) estimates the weights in a standard loss function over the Volcker-Greenspan period and finds evidence for interest rate variability in addition to the smoothing objective. Moreover, the estimated weight on the interest rate variability (0.70) in

[24] See also, e.g., Geweke and Amisano (2010) and Warne, Coenen and Christoffel (2012) on model comparison based on the predictive likelihood. Del Negro and Schorfheide (2008) alternatively propose the quasi-likelihood approach, where priors for the shocks are elicited from the predictive distribution of the observed endogenous variables.

[25] Note that we do not make the comparison with the Taylor rule interest rate since this does not have an immediate reference value based on actual data.

Ilbas (2012) is higher than those obtained for the smoothing (0.66) and output gap component (0.62). We therefore re-estimate the loss function specification (21), where we replace the interest rate smoothing term by the interest rate level.

The estimation yields a value of 0.45 for the Taylor rule, a value of 0.17 on the output gap and 0.55 on inflation, which are values similar to those obtained previously with the loss function including a smoothing term. The estimated weight on the interest rate level is 0.34. The empirical fit, however, turns out to be worse than in our specification of the loss function (21); the marginal likelihood value, corrected for prior effects, is -363.24, which is lower than the value reported for the case of (21) in Table 3.

4.3.2 Replacing the Taylor rule term by the interest rate level

One might suspect the Taylor rule term in (21) to capture the preference to stabilize interest rate variability in addition to interest rate smoothing, and that the absence of interest rate variability as a separate objective could be picked up by the Taylor rule instead. We therefore estimate the following loss function, where we replace the Taylor rule term by interest rate variability:

$$L_t = {\pi_t}^2 + q_y(y_t - y_t^p)^2 + q_{rd}(r_t - r_{t-1})^2 + q_{rl}{r_t}^2 \tag{22}$$

While the estimated parameters remain largely unaffected, we find that the empirical fit of the model under this loss function specification again worsens, yielding a marginal likelihood, computed with the training sample method, of -354.18, which is lower than in the case where the Taylor rule is present in the loss function.[26]

4.3.3 Replacing the Taylor (1993) rule by (i) the Taylor (1999) rule and (ii) the Taylor rule estimated with OLS

We have focused on the original Taylor rule because this is the most well-known and widely used cross-check. This rule may, however, not be the only rule used in monetary policy assessments. Yellen (2012) also refers to an alternative specification of the Taylor rule, suggested by Taylor (1999), where the coefficient on the output gap is 1.0 instead of 0.5. We have estimated the model for the period 1999:1 - 2007:4 with the Taylor (1999) rule replacing the Taylor (1993) rule. Since the two rules are quite similar, the results are not very differerent. The weight on the Taylor (1999) rule becomes somewhat smaller than on the Taylor (1993) rule, and the weight on output in the loss function decreases slightly, as expected. Overall, the model with the original Taylor (1993) rule has a slightly better empirical fit than the model with the Taylor (1999) rule, as measured by their marginal likelihood values, which are -251.03 and -255.40, respectively.

The aim for including the original Taylor (1993) rule in the loss function (21) is that it serves as a normative benchmark which policy makers take into account in making their decisions rather than to include a rule that fits the actual interest rate as closely as possible. However, one possible objection to our (interpretation of the) results is that the Taylor rule is known to fit

[26] The fit also worsens when we consider both the Taylor rule and the interest rate level in the loss function simultaneously, i.e., the loss function $L_t = (\pi_t - \bar{\pi})^2 + q_y(y_t - y_t^p)^2 + q_{rd}(r_t - r_{t-1})^2 + q_{rl}{r_t}^2 + q_T(r_t - r_t^T)^2$.

the Fed's behavior relatively well over the sample period, and if the model is misspecified, finding a positive weight on the Taylor rule in the loss function might reflect the model misspecification and not necessarily policy preferences. If this were the case, one would expect that replacing the original Taylor rule by an estimated Taylor rule that fits the data even better would yield an even higher weight on the rule and a better empirical fit of the model. We therefore estimate the Taylor rule with OLS over the estimation sample in order to investigate whether the empirical success of the model characterised by the loss function (21), and the estimated weight on the rule in the loss function, would increase when we consider the estimated rule. Following coefficients are obtained through the OLS procedure:

$$r_t^{OLS} = 1.74\pi_t + 0.73(y_t - y_t^p) \tag{23}$$

Although the OLS-coefficients turn out to be close to the original Taylor rule values, when we plug in this rule in the loss function (21) and estimate the model, we find that the weight on the rule decreases to 0.35 (from a weight of 0.42 on the original Taylor rule), while the empirical fit worsens from the previous marginal likelihood value of −333.10 to −355.77. Therefore, we consider this result as additional evidence in favor of the original Taylor (1993) rule as the one that has been used in practice as a normative benchmark, as suggested by Kahn (2012) based on FOMC transcripts.

4.3.4 Robustness to alternative output gap measures

In this section, we explore the effects on the estimation results of replacing the output gap based on the HP-filter as observable by two alternative output gap measures: (i) the CBO output gap measure and (ii) the (shorter) sample on the historical Greenbook estimates. Table 5 compares the results for the estimates of the loss function parameters. As the table shows, the estimates change very little when alternative observables are considered. This conclusion also holds for the remaining structural parameters in the model. Therefore, the conclusions drawn previously from the results obtained with the HP-based measure of the output gap would still hold if we had considered one of these alternative measures.

[Insert Table 5]

Figure 1 provides a visual comparison of the three alternative empirical output gap measures.[27] The vertical shaded areas represent the NBER recession periods. The measures based on the HP and the CBO estimates are overall similar, and follow closely the patterns of the output gap computed by Justiniano, Primiceri and Tambalotti (2011), while the Greenbook estimate seems to lead these two measures somewhat over most part of the sample for which data is available.

[Insert Figure 1]

[27] Note that, even if we do not use data beyond 2007:4 in the estimation exercises, we use all available data in the figure, and evaluate the model up to 2010:1. We also include the presample period in the figure for completeness.

4.4 Assessing the Fed's policy prior to the financial crisis

Much about the debate about the Fed's monetary policy prior to the financial crisis has focused on the expansionary policy during the years 2001 - 2006. Given that the modeling framework adopted in this paper largely captures the mainstream assumptions by policy makers regarding the structural economy and, in particular, the limited concerns about financial linkages at the time, we perform a counterfactual exercise to shed more light on the stance of monetary policy during the period 2001 - 2006. Figure 2 shows the actual Federal Fund's Rate, the rate implied by the classical Taylor rule, and the rate implied by optimal policy given by the estimated model. The US economy went into a recession in 2001, and the Fed cut the interest rate sharply, and more than prescribed by the Taylor rule. The gap with respect to the Taylor rule widened further around 2003, where the Federal Fund's Rate was cut further, while the Taylor rate remained constant or increased somewhat. The widening of the gap between the Taylor rule and the actual rate in 2003 led Taylor (2012) to conclude that the rule-based policy was abandoned by the Fed around this point in time, and denoted the post-2003 period as the "*Ad Hoc Era*".

[Insert Figure 2]

When assessing policy using a simple rule as a normative benchmark, it is important to note that also proponents of simple interest rate rules recommend that they should be used as guidelines and not followed mechanically. The central bank should thus deviate from a simple rule when it has good reasons to do so. The question is then which factors could explain the large deviations from the Taylor rule, and whether such deviations were warranted. Generally, optimal deviations from a simple rule depend on the shocks hitting the economy. As mentioned in the introduction, the classical Taylor rule may be better suited for supply shocks than for demand shocks, since monetary policy should respond more aggressively to demand shocks than implied by the Taylor rule, as such shocks give little or no trade-off between inflation stabilization and output stabilization. We have therefore decomposed the shocks in the estimated model and grouped them into four categories:

- Supply shocks: total factor productivity shock (ε_t^a), labor supply shock (ε_t^{lab}),
- Demand shocks: consumption (risk-premium) shock (ε_t^b), investment shock[28] (ε_t^i), exogenous spending shock (ε_t^g),
- Monetary policy shock: ε_t^m,
- Mark-up shocks: price mark-up shock (ε_t^p), wage mark-up shock (ε_t^w),

Although the monetary policy shock can be classified as a demand shock, it is useful to consider this separately, since this shock represents deviations from the estimated reaction pattern and is relevant when assessing the Fed's policy.

[28] The investment shock is classified here as a demand shock in that it pushes output and inflation in the same direction.

[Insert Figure 3]

Figure 3 shows how the estimated historical shocks affected the interest rate. We see that in the period 2001 - 2006, there were large negative demand shocks hitting the economy. The optimal response to these shocks is a very expansionary monetary policy, and as noted in the introduction, the Fed staff's view was that the coefficient on the output gap in the Taylor rule was too small for handling demand shocks. This view is confirmed in our analysis, as Figure 2 shows that there is a substantial discrepancy between the interest rate implied by the Taylor rule and the optimal interest rate, which is defined as the one that minimizes the estimated loss function, but where the monetary policy shock is set to zero. Thus, despite being derived from a loss function with a considerable weight on the Taylor rule, our model implies that it is optimal to deviate substantially from the Taylor rule when there are such large demand shocks.

Comparing the actual Fed fund's rate with the Taylor rule and the optimal interest rate, we see that although the Fed fund's rate was substantially lower than the Taylor rule, it was actually *higher* than the optimal interest rate in the period 2001 - 2006. The question of why the Fed set the interest rate so much lower than the Taylor rule can therefore be countered with the question of why it set the rate higher than what was optimal according to our estimated model and policy preferences. Based on the estimated model, a lower interest rate than the one actually set would have contributed to more stability in output and inflation, at least from an *ex ante* perspective. By construction, there was thus a (persistent) positive monetary policy shock in this period. Since the monetary policy shock is unexplained in our model, one could interpret the shock as either a "policy error", or alternatively representing policy judgments that capture factors not represented in the model, e.g., financial stability considerations.

Note that the optimal interest rate in Figure 2 is based on the estimated preference function with a weight of 0.42 on the Taylor rule. Thus, the large deviation from the Taylor rule did not represent a shift away from the Taylor rule. Indeed, if we estimate the model and the preference function on a sample ending in 2002 versus the full sample, the estimated weight on the Taylor rule is somewhat larger in the full sample, suggesting that, if anything, there was a increase in the weight on the Taylor rule.[29] Thus, we do not find any support for Taylor's (2012) claim that the Fed abandoned the Taylor rule around 2003. The large deviations from the Taylor rule were, according to our model, optimal deviations for a given weight on the Taylor rule, as a consequence of the presence of large negative demand shocks. These conclusions are in line with the findings of Groshenny (forthcoming), which attributes deviations of the policy rate from the Taylor rule to demand shocks hitting the economy in the period 2002:1-2006:4.

5 Conclusion

When John Taylor first introduced his rule, it was calibrated to match actual policy. However, later it has been used as a normative benchmark in policy discussions, both by Taylor and

[29] When we estimate the model with loss function specification (21) over the sample limited to 2002:4, we find an estimated weight of 0.39 (posterior mean) on the Taylor rule. Hence, although other Taylor-type rules have been used by policymakers as cross-checks, the original version seems to have remained an important, normative benchmark.

others. In this paper, we show that the Taylor rule has had an important influence on US monetary policy decisions over the last two decades. We estimate a version of the Smets and Wouters (2007) model over the period 1990:1-2007:4, where monetary policy is assumed to minimize a modified loss function, i.e., the weighted average of a standard loss function and the deviation of the policy rate from a predescribed Taylor rule. The results suggest that keeping the policy rate close to the levels implied by the Taylor rule has been the most important concern for policy makers after the inflation target. A comparison of the empirical fit of the modified loss function against a standard loss function shows that the former performs better, hence providing empirical support for the Taylor rule as an important input in monetary policy decisions. This finding implies that approaching the monetary policy process as optimal, where deviations of the policy rate from the Taylor rule are penalized, is a good description of US monetary policy, and confirms the indirect evidence based on FOMC transcripts, minutes of meetings and speeches reported in Kahn (2012).

The large deviations between the Fed fund's rate and the Taylor rule in the period 2001 - 2006 can be regarded as optimal deviations due to the existence of large negative demand shocks. Moreover, during the years prior to the financial crisis, the Fed fund's rate was somewhat higher than the optimal policy based on the estimated loss function with a weight on the Taylor rule.

Our analysis is conducted within a standard DSGE model without financial frictions. The argument for this is that during the period we consider, this type of models might have represented well the judgments of the policymakers regarding the workings of the economy. However, if the policymakers were aware of financial frictions and took them adequately into account when setting the interest rate, estimating the policy preferences within a model without financial frictions could bias the results. An interesting topic for future research is therefore to estimate the policy preferences within the type of DSGE models including a role for financial frictions that are currently being developed.

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Appendix I : Data Appendix

Following series are used as observables: real GDP, potential GDP, consumption, investment, hours worked, real wages, GDP deflator and the federal funds rate. The source of the series on GDP, nominal personal consumption and fixed private is the Bureau of Economic Analysis database of the US Department of Commerce. Real GDP is expressed in terms of 1996 chained dollars and the potential GDP is computed as the HP-trend of the real GDP. Consumption and investment are deflated with the GDP deflator. The log difference of the Implicit price deflator is used to compute inflation. Hours worked and hourly compensation for the non farming business sector for all persons are obtained from the Bureau of Labor Statistics. Real wage is computed by dividing the latter series by the GDP price deflator. The average hours index is multiplied with Civilian Employment figures of 16 years and over in order to correct for the limited coverage of the non farming business sector with respect to the GDP. The federal funds rate is downloaded from the FRED database of the Federal Reserve Bank of St-Louis. Inflation and interest rate are expressed in quarterly frequency. Remaining variables are expressed in 100 times log. In order to express the real variables in per capita terms, we divide them by the population over 16. All series are seasonally adjusted. The CBO measure of the output gap is obtained from the CBO, and the Greenbook estimates for the output gap are taken from the website of the Federal Reserve Bank of Philadelphia.

Appendix II : Prior Assumptions

Following Smets and Wouters (2007), we fix the annual depreciation rate on capital at 10 percent, i.e., $\delta = 0.025$, the ratio of exogenous spending to GDP, g_y, at 0.18, the mark-up in the labor market in the steady state (λ_w) at 1.5 and the curvature of the Kimball aggregator in both goods and labor markets (ε_p and ε_w) at 10. The monetary policy discount factor ς in equation (13) is fixed to the value of 0.99. The prior assumptions for the remaining parameters are reported in Table 6.

[Insert Table 6]

The priors for the structural parameters are in line with those of Smets and Wouters (2007). The standard errors of the error terms, except for the error in the first order condition of the interest rate, are assumed to have an inverted gamma distribution with 2 degrees of freedom and a mean of 0.10. The shock to the first order condition of the interest rate is assumed to have a mean of 0.3. As in Ilbas (2012), we base this prior on the results provided in Dennis (2006) for a similar shock to the first order condition of the interest rate. The persistence parameters of all shock processes, including the shock to the first order condition of the interest rate, and the MA coefficients are assumed to have a beta distribution with a prior mean of 0.5 and a prior standard error of 0.2. The steady state inflation rate is assumed to be gamma-distributed with a quarterly mean of 0.62% and standard error of 0.1, as in Smets and Wouters (2007).

The standard policy preference parameters in the loss function of monetary policy, i.e., q_y and q_{rd}, are restricted to positive values and assumed to have a gamma distribution with a mean of 0.5 and standard error of 0.1. Given that we have no prior information on the possible values for the weight on deviations of the policy rate from its value implied by the standard Taylor rule, i.e., q_T, it is a challenging task to impose a strong prior belief regarding this parameter. Therefore, we assume it to be uniformly distributed with a lower bound of 0.1 and an upper bound of 0.6. The choice of a (strictly) positive lower bound is based on the indirect evidence provided by Kahn (2012) that suggests for a positive value for q_T. The upper bound is chosen in order to impose a prior mean of around one third. A higher mean of around 0.5, for example, would reflect that we expect the Taylor rule to be equally important as the inflation target, which is not the case.[30]

[30] We however checked for the robustness of the estimation results by imposing a bound equal to $[0-1]$, which leaves the estimation results of both the structural and the policy parameters largely unaffected.

Table 1: **Estimation results under extended loss function**

Marginal Likelihood (MHM)	-402.52		
	mode	mean	lower - upper
structural parameters			
φ investment adjustment cost	4.43	5.23	$2.93 - 7.45$
σ_c intertemp. elast. of substitution	1.69	1.79	$1.38 - 2.19$
λ habit persistence	0.47	0.49	$0.35 - 0.63$
ξ_w Calvo wage stickiness	0.71	0.66	$0.52 - 0.81$
σ_l elast. of labor wrt real wage	3.89	3.83	$2.79 - 4.86$
ξ_p Calvo price stickiness	0.86	0.84	$0.79 - 0.90$
ι_w wage indexation	0.54	0.53	$0.28 - 0.77$
ι_p price indexation	0.34	0.35	$0.12 - 0.57$
ψ capital utiliz. cost	0.12	0.14	$0.06 - 0.21$
ϕ_p (1+fixed costs in production)	1.58	1.61	$1.47 - 1.75$
$(\beta^{-1} - 1)100$ const. discount	0.18	0.22	$0.08 - 0.36$
L_* constant labor supply	0.62	0.88	$-0.72 - 2.46$
$\bar{\gamma}$ constant growth rate	0.40	0.41	$0.36 - 0.47$
α share of capital in production	0.34	0.35	$0.30 - 0.40$
shock processes			
σ_a technology	0.12	0.13	$0.09 - 0.16$
σ_b risk premium	0.10	0.11	$0.07 - 0.14$
σ_g exogenous spending	0.39	0.41	$0.33 - 0.48$
σ_l investment specific	0.43	0.44	$0.34 - 0.54$
σ_p price mark-up	0.15	0.13	$0.08 - 0.17$
σ_w wage mark-up	0.74	0.57	$0.03 - 0.84$
σ_m shock FOC int. (opt.pol.)	0.26	0.28	$0.23 - 0.33$
σ_{lab} labor supply shock	0.09	0.21	$0.03 - 0.50$
σ_{ew} meas. error wages	1.41	1.42	$1.16 - 1.67$
ρ_a AR(1) technology	0.99	0.99	$0.98 - 0.99$
ρ_b AR(1) risk premium	0.72	0.69	$0.48 - 0.92$
ρ_g AR(1) exogenous spending	0.96	0.96	$0.93 - 0.98$
ρ_l AR(1) investment specific	0.66	0.66	$0.55 - 0.77$
ρ_p AR(1) price mark-up	0.67	0.58	$0.30 - 0.85$
ρ_w AR(1) wage mark-up	0.40	0.46	$0.14 - 0.86$
ρ_{ga} effect of technology on exports	0.15	0.23	$0.03 - 0.42$
μ_p MA(1) price mark-up	0.86	0.68	$0.31 - 0.94$
μ_w MA(1) wage mark-up	0.76	0.62	$0.32 - 0.94$
ρ_m AR(1) FOC int. (opt.policy)	0.91	0.91	$0.86 - 0.96$
ρ_{lab} AR(1) labor supply	0.86	0.74	$0.46 - 0.95$
ρ_{ew} AR(1) meas. error	0.90	0.90	$0.84 - 0.96$
monetary policy parameters			
$\bar{\pi}$ const. inflation	0.56	0.54	$0.45 - 0.63$
q_y pref. output gap	0.25	0.26	$0.17 - 0.35$
q_{rd} pref. int. smooth.	0.65	0.67	$0.51 - 0.84$
q_T pref. Taylor rule	0.41	0.42	$0.30 - 0.56$

Note: The table reports the marginal likelihood (modified harmonic mean) and the posterior estimation results (the posterior mode, the posterior mean and the 90% confidence bounds) for the parameters under the assumption that monetary policy follows a flexible inflation targeting regime where additional attention is paid to deviations of the policy instrument from a predescribed Taylor rule. Hence, the minimized period loss function is assumed to be: $(1 - q_T)[{\pi_t}^2 + q_y(y_t - y_t^p)^2 + q_{rd}(r_t - r_{t-1})^2] + q_T(r_t - r_t^T)^2$, where $r_t^T = 1.5\pi_t + 0.5(y_t - y_t^p)$. The posterior estimation results are obtained with the Metropolis-Hastings sampling algorithm based on $600,000$ draws, from which the first 20% draws are discarded. The posterior mode is obtained from the numerical optimization of the posterior kernel.

Table 2: **Estimation results under standard loss function**

Marginal Likelihood (MHM)	-413.41		
	mode	mean	lower - upper
structural parameters			
φ investment adjustment cost	5.70	6.18	$4.09 - 8.15$
σ_c intertemp. elast. of substitution	1.93	1.92	$1.51 - 2.34$
λ habit persistence	0.63	0.62	$0.51 - 0.74$
ξ_w Calvo wage stickiness	0.70	0.67	$0.52 - 0.82$
σ_l elast. of labor wrt real wage	3.60	3.44	$2.30 - 4.59$
ξ_p Calvo price stickiness	0.84	0.86	$0.82 - 0.91$
ι_w wage indexation	0.54	0.53	$0.28 - 0.78$
ι_p price indexation	0.31	0.38	$0.16 - 0.61$
ψ capital utiliz. cost	0.13	0.15	$0.06 - 0.22$
ϕ_p (1+fixed costs in production)	1.59	1.60	$1.46 - 1.74$
$(\beta^{-1} - 1)100$ const. discount	0.21	0.26	$0.10 - 0.43$
L_* constant labor supply	0.97	0.83	$-0.97 - 2.67$
$\bar{\gamma}$ constant growth rate	0.39	0.41	$0.35 - 0.48$
α share of capital in production	0.32	0.33	$0.28 - 0.38$
shock processes			
σ_a technology	0.16	0.17	$0.12 - 0.22$
σ_b risk premium	0.12	0.12	$0.08 - 0.16$
σ_g exogenous spending	0.35	0.37	$0.30 - 0.44$
σ_l investment specific	0.43	0.44	$0.34 - 0.54$
σ_p price mark-up	0.12	0.14	$0.10 - 0.18$
σ_w wage mark-up	0.04	0.16	$0.02 - 0.34$
σ_m shock FOC int. (opt.pol.)	0.27	0.29	$0.21 - 0.36$
σ_{lab} labor supply shock	0.50	0.50	$0.33 - 0.75$
σ_{ew} meas. error wages	1.39	1.41	$1.16 - 1.65$
ρ_a AR(1) technology	0.99	0.99	$0.97 - 0.99$
ρ_b AR(1) risk premium	0.61	0.61	$0.39 - 0.85$
ρ_g AR(1) exogenous spending	0.96	0.96	$0.94 - 0.98$
ρ_l AR(1) investment specific	0.70	0.68	$0.58 - 0.79$
ρ_p AR(1) price mark-up	0.61	0.47	$0.19 - 0.73$
ρ_w AR(1) wage mark-up	0.49	0.73	$0.34 - 0.96$
ρ_{ga} effect of technology on exports	0.13	0.20	$0.03 - 0.37$
μ_p MA(1) price mark-up	0.56	0.70	$0.32 - 0.94$
μ_w MA(1) wage mark-up	0.50	0.42	$0.09 - 0.71$
ρ_m AR(1) FOC int. (opt.policy)	0.92	0.91	$0.86 - 0.97$
ρ_{lab} AR(1) labor supply	0.50	0.33	$0.03 - 0.70$
ρ_{ew} AR(1) meas. error	0.91	0.91	$0.85 - 0.96$
monetary policy parameters			
$\bar{\pi}$ const. inflation	0.59	0.60	$0.54 - 0.66$
q_y pref. output gap	0.26	0.28	$0.19 - 0.36$
q_{rd} pref. int. smooth.	0.69	0.72	$0.58 - 0.88$

Note: The table reports the marginal likelihood (modified harmonic mean) and the posterior estimation results (the posterior mode, the posterior mean and the 90% confidence bounds) for the parameters under the assumption that monetary policy follows a standard flexible inflation targeting regime where the minimized period loss function is assumed to be: ${\pi_t}^2 + q_y(y_t - y_t^p)^2 + q_{rd}(r_t - r_{t-1})^2$. The posterior estimation results are obtained with the Metropolis-Hastings sampling algorithm based on $400,000$ draws, from which the first 20% draws are discarded. The posterior mode is obtained from the numerical optimization of the posterior kernel.

Table 3: **Comparison of empirical fit**

	Standard Loss	**Loss incl. Taylor Rule**
Marginal Likelihood (MHM)	−413.41	−402.52
MHM(1985:1-2007:4) - MHM(1985:1-1989:4)	−362.17	−333.10

Note: The first row of the table reports the marginal likelihood (modified harmonic mean) based on the estimation results reported in Tables 1 and 2. The second row reports the difference between the MHM computed for the period 1985:1-2007:4 (hence the training sample period and the estimation period combined, i.e., the full sample) and the MHM computed for the period 1985:1-1989:4 (i.e., the training sample). The first column corresponds to the case where monetary policy is assumed to follow a standard flexible inflation targeting regime with the loss function defined as: ${\pi_t}^2 + q_y(y_t - y_t^p)^2 + q_{rd}(r_t - r_{t-1})^2$. The second column corresponds to the case where monetary policy follows a flexible inflation targeting regime with additional weight assigned to deviations of the policy instrument from a predescribed Taylor rule: $(1-q_T)[{\pi_t}^2 + q_y(y_t - y_t^p)^2 + q_{rd}(r_t - r_{t-1})^2] + q_T(r_t - r_t^T)^2$, where $r_t^T = 1.5\pi_t + 0.5(y_t - y_t^p)$.

Table 4: **Model comparison based on volatilities of target variables**

		Standard Loss	**Loss w. Taylor Rule**
	Actual (data)	Model	Model
standard errors			
inflation	0.27	0.20	0.25
output gap	1.09	1.21	1.03
interest rate difference	0.12	0.18	0.11

Note: The table shows the actual standard errors of the target variables output gap, inflation and the interest rate difference, followed by the model-implied standard errors under the flexible inflation targeting regime with the loss function defined as: ${\pi_t}^2 + q_y(y_t - y_t^p)^2 + q_{rd}(r_t - r_{t-1})^2$ and under the flexible inflation targeting regime with additional weight assigned to deviations of the policy instrument from a predescribed Taylor rule:$(1-q_T)[{\pi_t}^2 + q_y(y_t - y_t^p)^2 + q_{rd}(r_t - r_{t-1})^2] + q_T(r_t - r_t^T)^2$, where $r_t^T = 1.5\pi_t + 0.5(y_t - y_t^p)$.

Table 5: **Robustness of loss function estimates to alternative output gap observables**

Observables for output gap	**HP**	**Greenbook**	**CBO**
$\bar{\pi}$ const. inflation (annualized)	2.16%	1.96%	2.04%
inflation $(1 - q_T)$	0.58	0.55	0.53
q_y output gap	0.15	0.17	0.16
q_{rd} interest rate smoothing	0.39	0.38	0.36
q_T Taylor rule	0.42	0.45	0.47

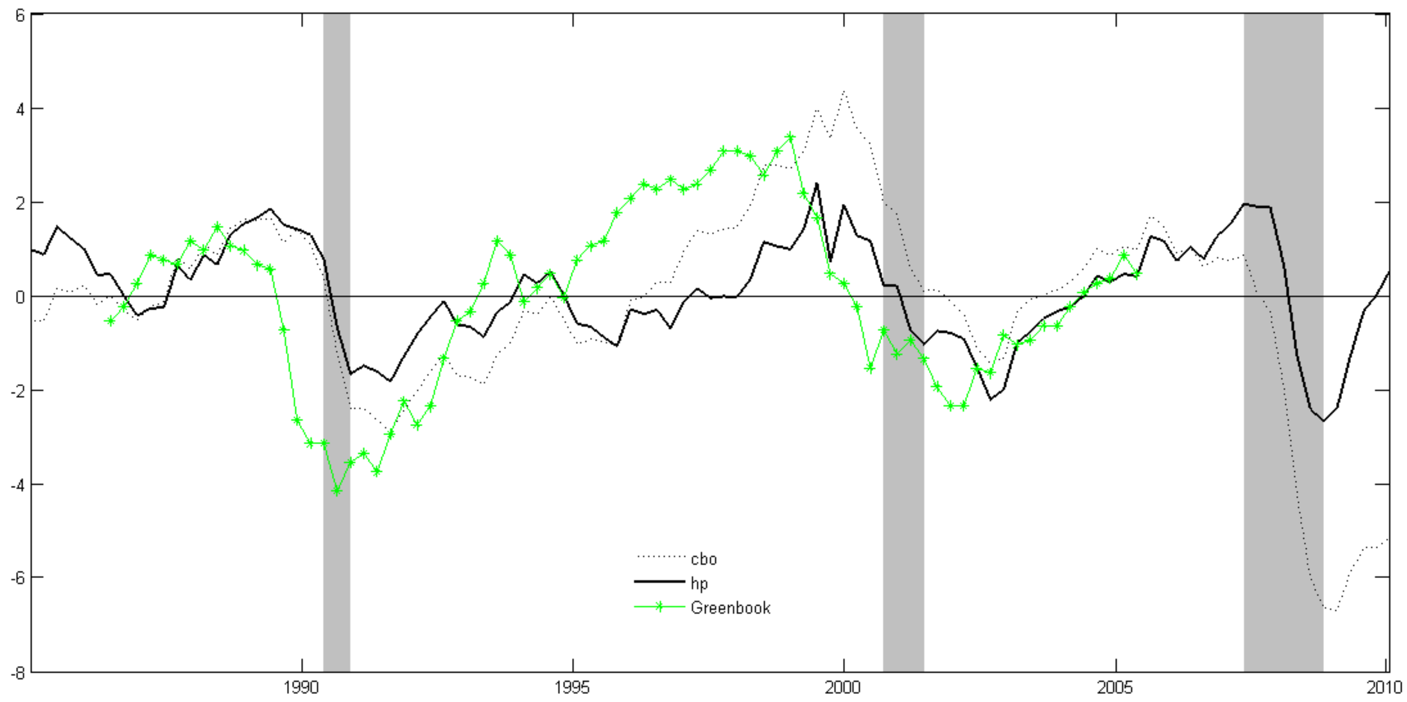
Note: The table compares the estimates of the optimal loss function parameters in $(1 - q_T)[{\pi_t}^2 + q_y(y_t - y_t^p)^2 + q_{rd}(r_t - r_{t-1})^2] + q_T(r_t - r_t^T)^2$ and constant inflation, obtained with the output gap observable based on the HP-filter, to the alternative measures based on the historical Greenbook estimates and the CBO measure.

Table 6: **Prior assumptions**

structural parameters	distrib.	mean	stand. dev.	**shock processes**	distrib.	mean	stand. dev.
φ investment adjustment cost	Normal	4	1.5	σ_a technology	InvGamma	0.1	2
σ_c intertemp. elast. of substitution	Normal	1.5	0.37	σ_b risk premium	InvGamma	0.1	2
λ habit persistence	Beta	0.7	0.1	σ_g exogenous spending	InvGamma	0.1	2
ξ_w Calvo wage stickiness	Beta	0.5	0.1	σ_l investment specific	InvGamma	0.1	2
σ_l elast. of labor wrt real wage	Normal	2	0.75	σ_p price mark-up	InvGamma	0.1	2
ξ_p Calvo price stickiness	Beta	0.5	0.1	σ_w wage mark-up	InvGamma	0.1	2
ι_w wage indexation	Beta	0.5	0.15	σ_{lab} labor supply	InvGamma	0.1	2
ι_p price indexation	Beta	0.5	0.15	σ_m shock FOC int. (opt.pol.)	InvGamma	0.3	2
ψ capital utiliz. cost	Beta	0.5	0.15	σ_{ew} meas. error	InvGamma	0.1	2
ϕ_p (1+fixed costs in production)	Normal	1.25	0.12	ρ_a AR(1) technology	Beta	0.5	0.2
$(\beta^{-1}-1)100$ const. discount	Gamma	0.25	0.1	ρ_b AR(1) risk premium	Beta	0.5	0.2
L_* constant labor supply	Normal	0	2	ρ_g AR(1) exogenous spending	Beta	0.5	0.2
$\bar{\gamma}$ constant growth rate	Normal	0.4	0.1	ρ_l AR(1) investment specific	Beta	0.5	0.2
α share of capital in production	Normal	0.3	0.05	ρ_p AR(1) price mark-up	Beta	0.5	0.2
				ρ_w AR(1) wage mark-up	Beta	0.5	0.2
				ρ_m AR(1) shock to opt.policy	Beta	0.5	0.2
monetary policy parameters				ρ_{ga} effect of techn. on exports	Beta	0.5	0.2
$\bar{\pi}$ SS inflation rate	Gamma	0.62	0.1	μ_p MA(1) price mark-up	Beta	0.5	0.2
q_y output gap	Gamma	0.5	0.1	μ_w MA(1) wage mark-up	Beta	0.5	0.2
q_{rd} interest rate smoothing	Gamma	0.5	0.1	ρ_{lab} AR(1) labor supply	Beta	0.5	0.2
q_T pref. Taylor rule	Uniform	0.35	0.14	ρ_{ew} AR(1) meas. error	Beta	0.3	0.2

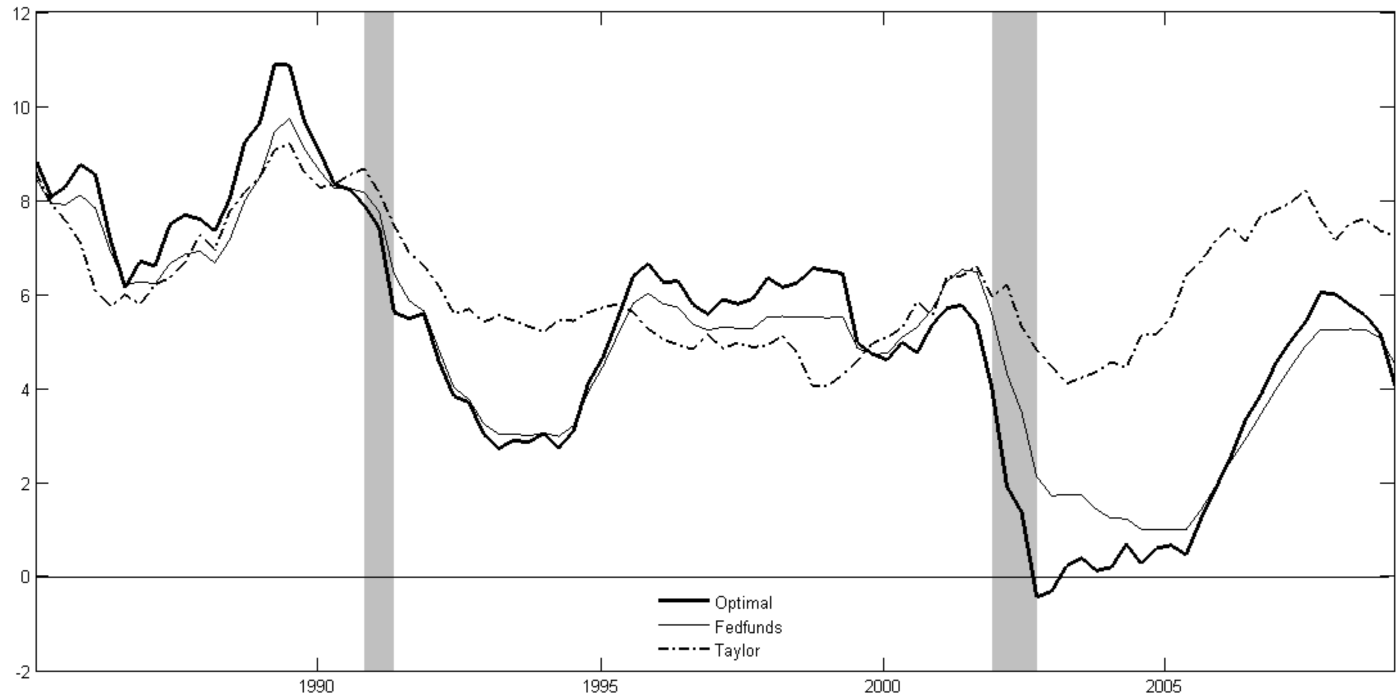
Note: The table shows the prior distribution, prior means and the prior standard errors for the structural parameters, the shock processes (where the standard errors of the shocks are denoted by σ and the AR (1) coefficients of the persistent shocks by ρ) and the monetary policy parameters.

Figure 1: **Comparison of alternative output gap measures (CBO, HP and Greenbook)**



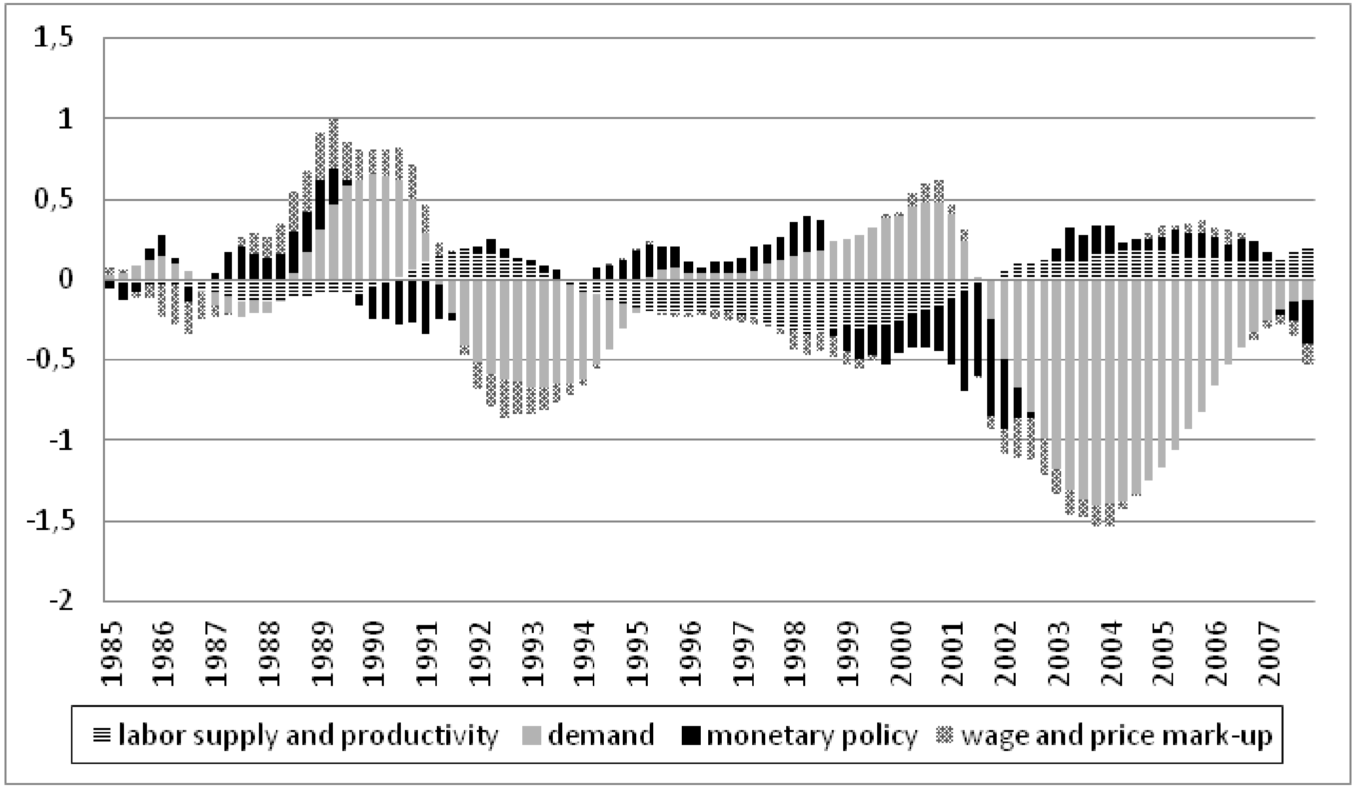
Note: The figure plots the alternative output gap measures for available data until 2010:1, although data is limited until 2007:4 to perform the estimation exercises. We also include the training sample period in the figure for completeness. The vertical shaded areas represent the NBER recession periods.

Figure 2: **Comparison of optimal interest rate, federal funds rate and the Taylor rule**



Note: The optimal interest rate is the model-implied, systematic, interest rate obtained after estimating the model under the assumption of optimal monetary policy, where the minimized period loss function is assumed to be: $(1-q_T)[{\pi_t}^2 + q_y(y_t - y_t^p)^2 + q_{rd}(r_t - r_{t-1})^2] + q_T(r_t - r_t^T)^2$. The figure further plots the implied Taylor rule obtained from the same model, and the actual federal funds rate. The vertical shaded areas represent the NBER recession periods.

Figure 3: **Historical decomposition of the interest rate**



Note: The figure shows the historical decomposition of the interest rate, where the shocks are grouped into four categories; monetary policy shock, demand shocks (risk-premium shock, investment shock and exogenous spending shock), supply shocks (total factor productivity shock and labor supply shock), and mark-up shocks (price and wage mark-up shocks).