American Economic Journal: Macroeconomics 2016, 8(3): 42–76
http://dx.doi.org/10.1257/mac.20150029

How Credible Is the Federal Reserve? A Structural Estimation of Policy Re-Optimizations†

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The paper proposes a new measure of the degree of credibility of the Federal Reserve. We estimate a medium-scale macroeconomic model, where the central bank has access to a commitment technology, but where a regime-switching process governs occasional re-optimizations of announced plans. The framework nests the commonly used discretion and commitment cases, while allowing for a continuum of intermediate cases. Our estimates reject both full-commitment and discretion. We instead identify occasional re-optimization episodes both before and during the Great Moderation period. Finally, through counterfactual analyses we assess the role of credibility over the past four decades. (*JEL* D78, E31, E32, E52, E58, E61)

Whether we have the credibility to persuade markets that we'll follow through is an empirical question.
—Ben Bernanke, Federal Reserve Chairman, September 13, 2012

Both academics and policymakers agree on the importance of central bank credibility in conducting monetary policy. Over the past few decades significant effort has been devoted to enhance credibility in monetary policy through the creation of independent central banks, the adoption of clear policy objectives, improved transparency and communication strategies, among other measures. Whether central banks are indeed credible, however, remains a largely open question. This paper proposes a novel measure of central bank credibility and provides new evidence about the credibility of the Federal Reserve over the past few decades.

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† Go to http://dx.doi.org/10.1257/mac.20150029 to visit the article page for additional materials and author disclosure statement(s) or to comment in the online discussion forum.

The term credibility is used in practice to refer to a multiplicity of different concepts.[1] Our definition of credibility coincides with the notion of "commitment," as in the seminal works of Kydland and Prescott (1977) and Barro and Gordon (1983). The presence of a policy trade-off (e.g., stabilizing inflation versus output), combined with the forward looking nature of economic agents, makes it desirable for the central bank to commit to a policy plan. By committing to a plan, the central bank can shape agents' expectations in a way that improves the short-run policy trade-offs. However, once those short-run benefits have been reaped, there is an ex post temptation to deviate from the original plan, and to re-optimize. Credibility is then defined as the ability to resist the temptation to re-optimize. This definition is widely accepted in the monetary policy literature, and is also consistent with the central bank having a "a history of doing what it says it will do," which both academics and policymakers selected as the most important factor in building central bank credibility in the survey by Blinder (2000).

The monetary policy literature has typically considered two alternative (and extreme) scenarios about the ability of the central bank to commit. It has either assumed that the central bank always follows its announced plans (commitment case), or that it always deviates (discretion case). Following Roberds (1987), Schaumburg and Tambalotti (2007), and Debortoli and Nunes (2010), this paper adopts a more flexible approach that nests commitment and discretion as special cases, while allowing for a continuum of intermediate cases—i.e., the so-called *loose commitment* setting.[2] The central bank has the ability to commit to its future plans, but it may occasionally give in to the temptation to revise its plans. Both the central bank and the private sector are aware of the possibility of policy re-optimizations, and take it into account when forming expectations. This setting is meant to capture the fact that central bankers understand the benefits of credibility, but at the same time there could be situations when a central bank disregards its commitments. These situations may arise because of changes in the dominating views within a central bank due to time-varying composition of its decision-making committee or outside pressures by politicians and the financial industry.[3]

In particular, we consider a model where the behavior of the central bank is described by a two-state regime-switching process. In each period, with probability γ the central bank follows its previous plan, while with probability $1-\gamma$ it makes a new plan. The probability $\gamma \in [0,1]$ can then be interpreted as a measure of credibility, in between the commitment ($\gamma = 1$) and discretion ($\gamma = 0$)

[1] As surveyed by Blinder (2000), academics and policymakers identify the term "credibility" with various different measures, such as "transparency," "independence," "aversion to inflation," etc.

[2] Roberds (1987) used the term "stochastic replanning" while Schaumburg and Tambalotti (2007) used the term "quasi-commitment."

[3] In the case of the United States, the reserve bank presidents serve one-year terms as voting members of the FOMC on a rotating basis, except for the president of the New York Fed. Furthermore, substantial turnover among the reserve bank presidents and the members of the Board of Governors arises due to retirement and outside options. With the (up to) seven members of the Board of Governors being nominated by the US President and confirmed by the US Senate, the composition of views in the FOMC may be affected by the views of the political party in power at the time of the appointment. Chappell, Havrilesky, and McGregor (1993) and Berger and Woitek (2005) find evidence of such effects in the United States and Germany, respectively. Also, the book by Havrilesky (1995) provides evidence on when politicians tried to influence monetary policy, and when the Federal Reserve did and did not respond.

extremes.[4] Using a regime-switching likelihood approach, we obtain an estimate of the (unconditional) probability of commitment, and identify specific episodes where the Federal Reserve has likely abandoned its commitments.

The empirical analysis is conducted within the medium-scale model for the US economy of Smets and Wouters (2007)—henceforth, SW. That model can be viewed as the backbone of the estimated models developed at central banks in recent years, and used for monetary policy analysis and forecasting. We depart from that model in two important ways. First, monetary policies are chosen optimally by a central bank operating under loose commitment, rather than being described by a simple (Taylor-type) rule. Second, we deal with a version of the SW model with regime-switching. In addition to the regime-switching process driving policy re-optimizations described earlier, we also allow the variance of the shock processes to shift over time to control for additional potential sources of time variation. Estimation is carried out using a Bayesian Markov Chain Monte Carlo (MCMC) algorithm.

Two main results emerge from the estimates. First, the model supports the idea that the Federal Reserve is to some extent credible, but that credibility is not perfect. This result differs from the existing literature, as it signals that both the commonly used assumptions of commitment and discretion are rejected by the data. Within a variety of different exercises, the posterior mode of the unconditional probability of commitment is estimated to be about 0.80, with fairly high precision.

Such a value could be viewed as closer to either commitment or discretion, depending on the metric used. In order to provide a clearer interpretation of our result, we perform counterfactual simulations in which the central bank is assumed to operate either under commitment or under discretion throughout the entire sample. This exercise highlights the importance of using our general framework; sometimes the dynamics of the economy are better described by the case of commitment, while at other times the case of discretion is better.

The second contribution of the article is the identification of historical episodes when the Federal Reserve likely abandoned its commitments, as measured by the (smoothed) probability of re-optimization. We find that policy re-optimizations likely occurred with the appointments of Arthur Burns and Paul Volcker but not with the appointments of Alan Greenspan and Ben Bernanke. Re-optimization episodes were also likely around changes in operating procedures of the Federal Reserve, specifically during the reserves targeting experiment conducted under Volcker in the early 1980s and the FOMC policy to start announcing the target for the Federal Funds rate around 1994. Additionally, we find a re-optimization episode in 2008, around the start of the quantitative easing policy under Bernanke. An alternative interpretation of our re-optimization episodes is to view them as a source of monetary policy shocks. According to this perspective, we find that typically the deviations from commitment during the 1970s implied policies that were relatively more expansionary, while deviations in the 1990s and 2000s implied policies that were relatively more contractionary.

[4] Equivalently, that probability can be thought of as a continuous variable measuring the durability of the Federal Reserve's promises, where longer durability corresponds to higher levels of credibility.

Alternative approaches to measure central banks' credibility have been proposed in the literature. For instance, through an index-based aggregation of information contained in bylaws and questionnaires, Cukierman (1992) develops some indicators of independence, transparency, and aversion to inflation. Also, as initially proposed in Svensson (1994), several studies have inferred a measure of "inflation-target" credibility by looking at the deviations of long-run inflation expectations from the central bank's inflation target. Here we study instead the role of credibility as a device to improve the policy responses to short-run economic disturbances.[5] As a result of these disturbances, temporary deviations of inflation expectations from target do not necessarily signal a credibility problem. In this respect, the advantage of our structural estimation approach is the possibility to disentangle commitment problems from other factors affecting agents' expectations.

Our work is also related to the empirical literature on optimal monetary policy. For the most part, that literature has abstracted from assessing the empirical plausibility of alternative commitment settings, by focusing either on commitment or discretion.[6] A few exceptions are the recent works of Givens (2012) and Coroneo, Corradi, and Monteiro (2013), who compare estimates of models with commitment and discretion, and conclude that the data favor the specification under discretion. Kara (2007) obtains a structural estimate of the degree of commitment through a least-squares estimation of a monetary policy rule obtained within the framework of Schaumburg and Tambalotti (2007), and provides evidence against the cases of commitment and discretion. In our framework the central bank's behavior regarding its previous commitment may change over time, with occasional switches between re-optimizations and continuations of previous plans. A complementary approach to ours is taken by Matthes (2015), who estimates a simple model where agents learn over time the probability that the central bank operates under commitment versus discretion, but abstracts from considering the actual behavior of the central bank. We argue instead that the Federal Reserve did not occasionally switch from commitment to discretion, but operated under loose commitment.[7] Also, Chen, Kirsanova, and Leith (2013) estimate a simple optimal monetary policy model under alternative commitment settings, allowing for switches in policy parameters. The authors conclude that the central bank increased its degree of conservatism after the 1970s, and operated under discretion. As opposed to that study, we conduct our analysis in a state-of-the-art DSGE model and with a richer dataset, and find empirical support for the idea that the Federal Reserve had some credibility, and only occasionally deviated from its commitments.

[5] As discussed in Clarida, Galí, and Gertler (1999), a central bank without commitment is not able to smooth over time the costs of economic fluctuations, thus giving rise to the so-called "stabilization bias." That concept needs to be distinguished from the "inflation bias" that arises when the central bank wishes to push output above its natural level because of long-run inefficiencies. See Ireland (1999) and Ruge-Murcia (2003) for empirical works related to that alternative source of time-inconsistency.

[6] Some examples are the works of Dennis (2004); Söderström, Söderlind, and Vredin (2005); Salemi (2006); Ilbas (2010); and Adolfson et al. (2011).

[7] As explained in detail in Section IVC, the behavior of the interest rate —and other variables as well— may not lie in between the commitment and discretion counterparts. Thus, our model generates different dynamics compared to one where agents' beliefs are formed taking an average between commitment and discretion.

Our setting is closely related to recent empirical studies in the DSGE regime-switching literature (see Liu, Waggoner, and Zha 2011; and Bianchi 2013) that analyze regime switches in the inflation target or in the coefficients of a monetary policy rule, while allowing the variances of the shocks to switch over time. The main difference with respect to those studies is that, in our model, the central bank formulates an optimal plan rather than following a simple interest rate rule. The restrictions implied by optimal policy under loose commitment allow us to distinguish policy re-optimization episodes from other types of regime switches.

The rest of the paper is organized as follows. Section I describes the baseline model, while Section II discusses the formulation of optimal policy in the loose commitment framework. Section III describes the estimation procedure, and Section IV outlines the main results. Section V provides some concluding remarks. Additional details regarding the robustness exercises are contained in separate appendices.

I. The Model

As discussed in the introduction, the distinctive feature of our model concerns the way monetary policy is designed. The underlying economy is instead described by a standard system of linearized equations

$$\mathbf{A}_{-1}\mathbf{x}_{t-1} + \mathbf{A}_0\mathbf{x}_t + \mathbf{A}_1 E_t\mathbf{x}_{t+1} + \mathbf{B}\mathbf{v}_t = \mathbf{0}, \tag{1}$$

where $\mathbf{x}_t$ denotes a vector of endogenous variables; $\mathbf{v}_t$ is a vector of zero-mean, serially uncorrelated, normally distributed exogenous disturbances; and $\mathbf{A}_{-1}$, $\mathbf{A}_0$, $\mathbf{A}_1$, and $\mathbf{B}$ are matrices whose entries depend (nonlinearly) on the model's structural parameters. The term E_t denotes the rational expectations operator, conditional on the information up to time t.

The analysis is conducted within the model of Smets and Wouters (2007). The model, based on the earlier work by Christiano, Eichenbaum, and Evans (2005) includes monopolistic competition in the goods and labor market, nominal frictions in the form of sticky price and wage settings, allowing for dynamic inflation indexation.[8] It also features several real rigidities—habit formation in consumption, investment adjustment costs, variable capital utilization, and fixed costs in production. The model describes the behavior of 14 endogenous variables: output (y_t), consumption (c_t), investment (i_t), labor (l_t), the capital stock (k_t), with variable utilization rate (z_t) and associated capital services (k_t^s), the wage rate (w_t), the rental rate of capital (r_t^k), the nominal interest rate (r_t), the value of capital (q_t), price inflation (π_t), and measures of price markups (μ_t^p) and wage markups (μ_t^w). The model dynamics are driven by six structural shocks: two shocks—a price markup (e_t^p) and wage markup (e_t^w) shock follow an ARMA(1,1) process, while the remaining four shocks—total factor productivity (e_t^a), risk-premium (e_t^b), investment-specific technology shock (e_t^i) and government spending shock (e_t^g) follow an AR(1) process. All the shocks are uncorrelated, with the exception of a positive correlation between

[8] Monopolistic competition is modeled following Kimball (1995), while the formulations of price and wage stickiness follow Yun (1996) and Erceg, Henderson, and Levin (2000).

government spending and productivity shocks, i.e., $\mathrm{Corr}(e_t^g, e_t^a) = \rho_{ag} > 0$.[9] The model can be cast into equation (1) defining $\mathbf{x}_t$ as a 22×1 vector containing all the variables described above (i.e., endogenous variables, structural shocks and corresponding MA components), and $\mathbf{v}_t$ as a vector containing the independently and identically distributed innovations to the structural shocks.

We depart from the original SW formulation in two fundamental ways. First, we account for changes in the volatility of the exogenous shocks. Recent studies (see Primiceri 2005, Sims and Zha 2006, and Cogley and Sargent 2006, among others) find that exogenous shocks have displayed a high degree of heteroskedasticity. For our purposes, ignoring this heteroskedasticity would potentially lead to inaccurate inference: the time variation in the volatility of the shocks could be mistakenly attributed to policy re-optimization episodes, thus biasing our measure of credibility. To deal with this issue, we model heteroskedasticity as a Markov-switching process

$$\mathbf{v}_t \sim N(\mathbf{0}, \mathbf{Q}_{s_t^{vo}}), \tag{2}$$

where the variance-covariance matrix $\mathbf{Q}_{s_t^{vo}}$ depends on an unobservable state, $s_t^{vo} \in \{h, l\}$, that differentiates between high- (h) and low- (l) volatility regimes. While in principle one could consider a process with more states, a specification with two states has been found to fit the data best in estimated regime-switching DSGE models (see Liu, Waggoner, and Zha 2011; and Bianchi 2013). The Markov-switching process for volatilities (s_t^{vo}) evolves independently from the regime-switching process that governs re-optimizations (s_t, described in detail in the next section). The transition matrix for s_t^{vo} is given by

$$\mathbf{P}^{vo} = \begin{bmatrix} p_h & (1-p_h) \\ (1-p_l) & p_l \end{bmatrix}. \tag{3}$$

The second and more important departure from the original SW model concerns the behavior of the central bank. Rather than including a (Taylor-type) interest rate rule, and the associated monetary policy shock, we explicitly solve the central bank's decision problem. As discussed in the next section, this allows us to describe the central bank's commitment problem, and to characterize the nature of policy re-optimizations. Throughout our analysis, it is assumed that the central bank's objectives are described by a (period) quadratic loss function

$$\mathbf{x}_t' \mathbf{W} \mathbf{x}_t \equiv \pi_t^2 + w_y \tilde{y}_t^2 + w_r (r_t - r_{t-1})^2. \tag{4}$$

Without loss of generality, the weight on inflation (π_t) is normalized to one so that w_y and w_r represent the weights on output gap ($\tilde{y}_t$) and the nominal interest rate (r_t) relative to inflation. Those weights will be estimated from the data. According to equation (4), the central bank's inflation target coincides with the steady-state level of inflation $\bar{\pi}$. The target for output is instead its "natural" counterpart, defined as the

[9] All the variables are expressed in deviations from their steady state. For a complete description of the model, the reader is referred to the original Smets and Wouters (2007) paper.

level of output that would prevail in the absence of nominal rigidities and markup shocks. This formulation is consistent with the natural rate hypothesis, i.e., that monetary policy cannot systematically affect average output. It is also consistent with the original SW specification, where because of price and wage indexation, the steady-state inflation does not produce any real effect. As a result, the central bank's credibility problems do not lead to an average inflation bias, but only to a stabilization bias in response to economic shocks, as illustrated in Clarida, Galí, and Gertler 1999.[10] The last term in the loss function $(w_r(r_t - r_{t-1})^2)$ indicates the central bank's preference for interest rate smoothing, as supported by the recent evidence of Coibion and Gorodnichenko (2012).

A common approach in the literature is to describe the central bank behavior through simple rules, that are known for their good empirical properties. Here we adopt a similar approach, and use a simple loss function that has been shown to realistically describe the behavior of the Federal Reserve (see e.g., Rudebusch and Svensson 1999, or more recently Ilbas 2010 and Adolfson et al. 2011). We then investigate to what extent the central bank was credible in implementing such empirically plausible objectives.

An alternative approach would be to consider a theoretical loss function consistent with the representative agent's preferences (see e.g., Benigno and Woodford 2012). However, there are several reasons why the central bank's objectives may not reflect the preferences of the underlying society. For instance, for all practical purposes it would be infeasible to specify the central bank's goals in terms of a utility-based welfare criterion, as it would include a very high number of targets in terms of variances and covariances of different variables.[11] Also, prominent scholars like Svensson (1999) argue that a simple mandate is more robust to model and parameter uncertainty than a complicated theoretical loss function.

Notice also that we are not dismissing the use of interest rate rules, neither from a normative nor from a positive perspective. We describe the central bank's decision process as a device to study commitment problems. The resulting policies could be implemented through targeting rules, or through appropriately defined interest rate rules, with clearly equivalent empirical implications.[12]

II. The Loose Commitment Framework

The system of equations (1) implies that current variables $(\mathbf{x}_t)$ depend on expectations about future variables $(E_t \mathbf{x}_{t+1})$. This gives rise to the time-inconsistency problem at the core of our analysis. The central bank's plans about the future course of policy could indeed have an immediate effect on the economy, as long as those plans are embedded into the private sector expectations. Having reaped the gains

[10] Notice, however, that since the markup shocks are allowed to follow an ARMA(1,1), the stabilization bias could potentially be very persistent, and could closely resemble an average inflation bias.

[11] For instance, the utility-based welfare criterion in the SW model contains more than 90 target variables. We verified that a version of the model with such a welfare criterion provides a much poorer empirical fit.

[12] Debortoli, Maih, and Nunes (2014) show that a simple Taylor rule $i_t = \phi_i i_{t-1} + \phi_\pi \pi_t + \phi_y \tilde{y}_t + \epsilon_t$ tracks very well the data generated by the SW model under loose commitment ($R^2 = 0.87$), and that the interest rate persistence ϕ_i increases with the degree of commitment.

from affecting expectations, the central bank has an ex post incentive to disregard previous plans, and freely set its policy instruments. The literature has typically considered one of two dichotomous cases to deal with the time-inconsistency problem: commitment or discretion. In this paper we use a more general setting that nests both these frameworks. Following Schaumburg and Tambalotti (2007) and Debortoli and Nunes (2010), it is assumed that the central bank has access to a *loose commitment* technology. In particular, the central bank is able to commit, but it occasionally succumbs to the temptation to revise its plans. Both the central bank and private agents are aware of the possibility of policy re-optimizations and take it into account when forming their expectations.

More formally, at any point in time monetary policy can switch between two alternative scenarios, governed by the unobservable state $s_t \in \{0;1\}$. If $s_t = 1$, previous commitments are honored. Instead, if $s_t = 0$, the central bank makes a new (state-contingent) plan over the infinite future, disregarding all the commitments made in the past. The variable s_t evolves according to a two-state stochastic process, with transition matrix

$$\mathbf{P} = \begin{bmatrix} \Pr(s_t = 1 | s_{t-1} = 1) & \Pr(s_t = 0 | s_{t-1} = 1) \\ \Pr(s_t = 1 | s_{t-1} = 0) & \Pr(s_t = 0 | s_{t-1} = 0) \end{bmatrix} = \begin{bmatrix} \gamma & 1-\gamma \\ \gamma & 1-\gamma \end{bmatrix}, \tag{5}$$

and where $\gamma \in [0,1]$. The limiting case where previous promises are always honored (i.e., $\gamma = 1$) coincides with the canonical commitment setting. Instead, if $\gamma = 0$ the central bank operates under discretion.

Notice that s_t constitutes an independent switching process, where $\Pr(s_t = j | s_{t-1} = 1) = \Pr(s_t = j | s_{t-1} = 0)$. In other words, honoring commitments in a given period does not make a policy re-optimization (or continuing plans) more or less likely in the future.[13] As a result, there is a direct and intuitive mapping between a single parameter of the model—the probability of commitment γ—and the degree of central bank's credibility: the higher is γ, the more credible is the central bank.[14]

As is common in the DSGE regime-switching literature, we maintain the assumption that s_t is an exogenous process. Accordingly, we are interpreting policy re-optimizations as exogenous shocks influencing the behavior of the central bank, in a similar fashion to common monetary policy shocks. The validity of this assumption could be questioned on the grounds that central banks may deliberately choose to abandon their commitments in specific situations, e.g., when unusually large shocks hit the economy.[15] That criticism would be especially valid if the central

[13] In standard monetary regime-switching models, a process like s_t displays instead some degree of persistence, capturing the fact that once a monetary regime (e.g., *Dovish* or *Hawkish*) takes office, it is likely to remain in power for a prolonged period of time.

[14] Such a mapping would be less straightforward if we were to adopt a more general Markov-Switching process. In that case, it would indeed be necessary to distinguish between conditional and unconditional measures of credibility, that would depend on two regime-switching probabilities. Also, following that approach would significantly complicate the solution to the central bank problem.

[15] Admittedly, it would be ideal to let policy re-optimizations depend on the model's state variables, as in Debortoli and Nunes (2010). That specification, however, requires adopting a nonlinear solution method, that would make our estimation exercise infeasible.

bank had to commit to strict targets for its variables of interest: it would be very costly, if not impossible, to achieve those targets in turbulent times. In our setting, however, the central bank has more flexibility. This is because the responses to the shocks $\mathbf{v}_t$ are always part of the central bank's state-contingent plan.[16] In that case, it is not obvious that deviations from the original plan should depend on the occurrence of particular shocks. In Section IVC, we provide some suggestive evidence supporting the validity of our assumption by performing Granger causality tests.

A. *The Central Bank's Problem and Policy Re-Optimizations*

The problem of the central bank when making a new plan can be written as

$$(6) \quad \mathbf{x}_{-1}'\mathbf{V}\mathbf{x}_{-1} + d = \min_{\{x_t\}_{t=0}^{\infty}} E_{-1}\sum_{t=0}^{\infty}(\beta\gamma)^t[\mathbf{x}_t'\mathbf{W}\mathbf{x}_t + \beta(1-\gamma)(\mathbf{x}_t'\mathbf{V}\mathbf{x}_t + d)]$$

$$(7) \quad \text{s.t.}\, \mathbf{A}_{-1}\mathbf{x}_{t-1} + \mathbf{A}_0\mathbf{x}_t + \gamma\mathbf{A}_1 E_t\mathbf{x}_{t+1} + (1-\gamma)\mathbf{A}_1 E_t\mathbf{x}_{t+1}^{reop} + \mathbf{B}\mathbf{v}_t = \mathbf{0} \;\; \forall t.$$

The terms $\mathbf{x}_{t-1}'\mathbf{V}\mathbf{x}_{t-1} + d$ summarize the value function at time t. Since the problem is linear-quadratic, the value function is given by a quadratic term in the state variables $\mathbf{x}_{t-1}$, and a constant term d reflecting the stochastic nature of the problem. The objective function is given by an infinite sum discounted at the rate $\beta\gamma$ summarizing the history in which re-optimizations never occur. Each term in the summation is composed of two parts. The first part $\mathbf{x}_t'\mathbf{W}\mathbf{x}_t$ is the period loss function. The second part $\beta(1-\gamma)(\mathbf{x}_t'\mathbf{V}\mathbf{x}_t + d)$ indicates the value the policymaker obtains if a re-optimization occurs in the next period. The sequence of constraints (7) corresponds to the structural equations (1), with the only exception that expectations of future variables are expressed as the weighted average between two terms: the allocations prevailing when previous plans are honored $(\mathbf{x}_{t+1})$, and those prevailing when a re-optimization occurs $(\mathbf{x}_{t+1}^{reop})$. This reflects the fact that private agents are aware of the possibility of policy re-optimizations, and take this possibility into account when forming their expectations.[17]

We solve for the Markov-Perfect equilibrium of the above economy, where the equilibrium choices $\mathbf{x}_{t+1}^{reop}$ only depend on natural state variables. We can thus express the expectations related to the re-optimizations state as $E_t\mathbf{x}_{t+1}^{reop} = \tilde{\mathbf{F}}\mathbf{x}_t$, where $\tilde{\mathbf{F}}$ is a matrix of coefficients to be determined, and is taken as given by the central bank.[18]

The presence of the (unknown) matrix $\tilde{\mathbf{F}}$ complicates the solution of the central bank problem. For any given $\tilde{\mathbf{F}}$, the solution to the central bank's problem can be derived using the recursive techniques described in Kydland and Prescott (1980) and Marcet and Marimon (2011). The associated system of first-order conditions could

[16] As a result, in our model the central bank does not face a trade-off between credibility and flexibility, as considered e.g., in Lohmann (1992).

[17] To simplify the notation, we have dropped regime dependence and replaced $\mathbf{x}_{t+1}|s_t = 0$ with the more compact term $\mathbf{x}_{t+1}^{reop}$.

[18] We are therefore ruling out the possibility of reputation and coordination mechanism as described, for instance, in Walsh (1995).

then be solved using a standard solution algorithm for rational expectations models (e.g., Sims 2002). However, a Markov-Perfect equilibrium additionally requires the matrix $\tilde{\mathbf{F}}$ to be consistent with the policies actually implemented by the central bank. This involves the solution of a fixed point problem.[19]

The solution to the central bank's problem takes the form

$$\begin{bmatrix} \mathbf{x}_t \\ \lambda_t \end{bmatrix} = \mathbf{F}_{s_t} \begin{bmatrix} \mathbf{x}_{t-1} \\ \lambda_{t-1} \end{bmatrix} + \mathbf{G} \mathbf{v}_t, \tag{8}$$

where λ_t is a vector of Lagrange multipliers attached to the constraints (7), with initial condition $\lambda_{-1} = \mathbf{0}$. In particular, the Lagrange multipliers λ_{t-1} contain a linear combination of past shocks $\{\mathbf{v}_{t-1}, \mathbf{v}_{t-2}, \ldots, \mathbf{v}_0\}$, summarizing the commitments made by the central bank before period t.[20] A policy re-optimization implies that previous commitments are disregarded so that the current variables are not affected by λ_{t-1}, or equivalently as if λ_{t-1} were reset to zero. Therefore, the effects of policy re-optimizations can be described by the state dependent matrices

$$\mathbf{F}_{(s_t=1)} = \begin{bmatrix} \mathbf{F}^{xx} & \mathbf{F}^{x\lambda} \\ \mathbf{F}^{\lambda x} & \mathbf{F}^{\lambda\lambda} \end{bmatrix} \qquad \mathbf{F}_{(s_t=0)} = \begin{bmatrix} \mathbf{F}^{xx} & \mathbf{0} \\ \mathbf{F}^{\lambda x} & \mathbf{0} \end{bmatrix}. \tag{9}$$

In particular, notice that the unobservable state s_t only affects the columns of the matrices $\mathbf{F}_{s_t}$ describing the responses to λ_{t-1}. On the contrary, the policy responses to the state variables $\mathbf{x}_{t-1}$ and to the shocks $\mathbf{v}_t$ remain the same, regardless of whether the central bank re-optimizes or not.

The above formulation highlights the nature of policy re-optimizations, and provides an intuition for how re-optimizations can be identified in the data. From a reduced-form perspective, a policy re-optimization implies that macroeconomic variables cease to depend on a subset of the historical data, summarized in our model by the vector λ_{t-1}, and thus display a lower degree of persistence. From a more structural perspective, policy re-optimizations could instead be viewed as a particular type of monetary policy shock, with an effect on the endogenous variables given by

$$\mathbf{e}_t^{reop} \equiv \mathbf{x}_t^{reop} - \mathbf{x}_t = -\mathbf{F}^{x\lambda} \lambda_{t-1}. \tag{10}$$

Notice, however, that while the timing of these "re-optimization shocks" is exogenous—as for standard monetary policy shocks—the sign and magnitude of their impact are instead endogenous, and depend on the history of past shocks summarized by λ_{t-1}. For example, if a re-optimization shock occurs when λ_{t-1} is large (small) the shock will have a large (small) impact on the economy. Thus, the effects

[19] Methods to solve for Markov-Perfect equilibria are described in Backus and Driffill (1985), Söderlind (1999), and Dennis (2007). Debortoli, Maih, and Nunes (2014) extended those methodologies to analyze loose commitment problems in large-scale models. The algorithm makes use of the fact that in equilibrium it must be that $\mathbf{x}_t^{reop} = \mathbf{F}^{xx}\mathbf{x}_{t-1} + \mathbf{G}_x \mathbf{v}_t$. Rational expectations then implies that $E_t \mathbf{x}_{t+1}^{reop} = \mathbf{F}_{xx}\mathbf{x}_t$. Thus, one must solve the fixed point problem, such that $\mathbf{F}_{xx} = \tilde{\mathbf{F}}$.

[20] For this reason, the Lagrange multipliers λ_t are often referred to as co-state variables.

of policy re-optimizations change over time. As discussed in Section IVC, this has implications for how the specific re-optimization episodes are identified in the data.

Our setting bears many similarities to some of the recent monetary regime-switching models (see e.g., Davig and Leeper 2007; Farmer, Waggoner, and Zha 2009; Liu, Waggoner, and Zha 2011; and Bianchi 2013)—a direct comparison with regime-switching interest rate rules is presented in Appendix A. As in those models, an exogenous shock governs switches from one regime to another, where the conduct of monetary policy is different. And as in those models, because of the forward-looking nature of economic agents, what happens under a certain regime depends on what the agents expect is going to happen under alternative regimes, and on the probability of switching to a new regime. This can be noticed from the fact that probability of commitment γ not only enters the transition matrix $\mathbf{P}$, but it also affects the matrices $\mathbf{F}_{s_t}$ and $\mathbf{G}$.

An important difference with respect to the existing regime-switching model is that our regimes are described by the same structural parameters.[21] In other words, modeling policy re-optimization does not require introducing any additional parameters, besides the switching probability γ. As indicated by equation (9), policy re-optimizations only impose specific zero-restrictions on the model's law of motion. These restrictions differentiate our policy re-optimizations from other types of regime switches, such as switches in Taylor rule parameters or changes in the inflation target that are typically considered in the literature. In fact, commitment problems could be viewed as one of the causes of the monetary regime switches typically found in these studies. Alternative candidates could be changes in the central bank's preferences—e.g., between a "Hawkish" to a "Dovish" monetary regime, or in other structural parameters. However, there is a fundamental difference between switches in policy preferences and commitment problems. Changes in policymaker's preferences imply a movement along the policy frontier, where reducing the volatility of one variable implies increasing the volatility of another variable. For instance, a switch from a "Dovish" to a "Hawkish" regime would bring about a lower volatility of inflation, at the expense of a higher volatility of output. Commitment problems instead worsen the policy trade-off (i.e., a movement of the policy frontier), such that both the volatility of output and inflation increase.[22] While our analysis abstracts from considering the specific sources of regime switches, our inferred re-optimizations episodes could be related to changes in members of FOMC, or to changes in the operating procedure of FOMC, as discussed in Section IVC.

[21] Note that since the same type of central bank is in power, our regime-switching framework does not display an indeterminacy problem as described in Farmer, Waggoner, and Zha (2009). There would need to be an additional layer of uncertainty or mismeasurement to give rise to the possibility of indeterminacy. For a further discussion on this issue see Barthelemy and Marx (2013).

[22] See Debortoli and Nunes (2014) for a comparison between the effects of switches in central banks' preferences, the effects of changes in Taylor-rule parameters, and the effects of loose commitment within a baseline New Keynesian model. Also see Lakdawala (2013) for an empirical study on continuous time-varying central bank preferences.

III. Estimation

For estimation, we combine the law of motion (8) with an observation equation, and obtain the system

$$\xi_t = \mathbf{F}_{s_t}\xi_{t-1} + \mathbf{G}\mathbf{v}_t \tag{11}$$

$$\mathbf{x}_t^{obs} = \mathbf{A} + \mathbf{H}\xi_t, \tag{12}$$

where $\mathbf{x}_t^{obs}$ denotes the observable variables, $\xi_t \equiv [\mathbf{x}_t, \lambda_t]'$, the matrix $\mathbf{H}$ maps the state variables into the observables, and $\mathbf{A}$ is a vector of constants. For comparability with SW, the model is estimated using the same seven quarterly US time series as observable variables: the log difference of real GDP, real consumption, real investment, the real wage, log hours worked, the log difference of the GDP deflator, and the federal funds rate. The monetary policy shock in SW is replaced by an indepedently and identically distributed measurement error, so that the number of shocks is the same as the number of observable variables. This is required to ensure that we have enough shocks to avoid the stochastic singularity problem in evaluating the likelihood.

The estimation is carried out using a Bayesian likelihood approach. The likelihood function for a standard DSGE model can be evaluated using the standard Kalman Filter. Given the regime-switching nature of our model, the standard Kalman filter needs to be augmented with the Hamilton (1989) filter, following the procedure described in Kim and Nelson (1999). The likelihood function is then combined with the prior to obtain the posterior distribution.

We estimate a total 42 parameters, while fixing 6 parameters.[23] Tables 1–3 summarize the priors used for the estimated parameters. For the common structural parameters as well as for the shock processes we use the same priors used in SW.[24] Regarding the three new parameters describing the central bank behavior, we proceed as follows. For the probability of commitment γ we use a uniform prior on the interval $[0, 1]$, as we do not want to impose any restrictive prior beliefs about whether the optimal policy is conducted in a setting that is closer to commitment or discretion. Thus the posterior of γ will be entirely determined by the data. For the loss function parameters w_y and w_r, we instead choose fairly loose Gamma priors. Using the procedure of Komunjer and Ng (2011), we checked that introducing these parameters does not alter the identification properties of the SW model, and that our three new parameters are (locally) identified. For our purposes, this implies that we are able to separately identify the endogenous persistence due to commitment, from the persistence due to an interest rate smoothing motive, as implied by w_r.

[23] As in SW, the depreciation rate δ is fixed at 0.025, spending-GDP ratio g_y at 18 percent, steady-state markup in the labor market at 1.5, and curvature parameters in the goods and labor markets at 10. We additionally fix the real wage elasticity of labor supply at $\sigma_l = 1$, as that parameter is estimated imprecisely in the original SW paper, and fixing it greatly improves the convergence of our estimation algorithm. In Appendix B, we show that our results are robust to adopting different values.

[24] In our model the regime switching variance specification introduces two values for the standard deviation of each shock, as well as two parameters of the transition matrix (P^{vo}).

Table 1—Prior and Posterior Distribution of Structural Parameters

	Parameter	Prior	Posterior			
			Mode	Mean	5%	95%
$\overline{l}$	Steady-state labor	Normal (0, 2)	0.243	0.234	0.213	0.253
$\overline{\pi}$	Steady-state inflation	Gamma (0.62, 0.1)	0.742	0.754	0.647	0.874
$\overline{\gamma}$	Growth rate	Normal (0.4, 0.1)	0.182	0.184	0.148	0.221
$\overline{\beta}$	Discount factor	Gamma (0.25, 0.1)	0.223	0.241	0.129	0.365
α	Capital income share	Beta (0.3, 0.05)	0.192	0.192	0.166	0.219
ψ	Capital capacity utilization	Normal (0.5, 0.15)	0.697	0.686	0.525	0.831
φ	Capital adjustment cost	Normal (4.0, 1.5)	6.316	6.532	5.084	8.125
σ_c	Risk aversion	Normal (1.5, 0.37)	1.771	1.766	1.488	2.091
h	Habit persistence	Beta (0.7, 0.1)	0.765	0.765	0.700	0.821
Φ	Fixed cost	Normal (1.25, 0.12)	1.614	1.600	1.490	1.714
ι_w	Wage indexation	Beta (0.5, 0.15)	0.500	0.527	0.316	0.734
ι_p	Price indexation	Beta (0.5, 0.15)	0.809	0.809	0.689	0.908
ξ_p	Price stickiness	Beta (0.5, 0.1)	0.783	0.775	0.727	0.822
ξ_w	Wage stickiness	Beta (0.5, 0.1)	0.626	0.619	0.539	0.695

Notes: The table reports the prior distribution (mean and standard deviation in parentheses) and the estimated posterior mean, mode, and fifth and ninety-fifth percentiles for the model structural parameters. $\overline{\beta}$ is equivalent to $(\beta^{-1} - 1)$ in SW.

The data sample in the baseline estimation runs from 1966:I–2012:II. There may be concern about using the data from 2007 onwards that includes the financial crisis and periods where the zero lower bound was binding. As a robustness check, we estimate the posterior mode of the model where the data sample does not include the financial crisis. Additionally we estimate the model using long-term interest rates (instead of the fed funds rate) which did not face the zero lower bound constraint. Finally, a conventional wisdom is that the Federal Reserve has been closer to full commitment since the appointment of Paul Volcker. To test this hypothesis, we estimate our model starting with data from 1979:III. In all these cases results are very similar to the baseline case—see Appendix B for a detailed illustration.

IV. Results

A. *Parameter Estimates*

Table 1 reports the priors and the posterior mode, mean, fifth and ninety-fifth percentiles for the structural parameters. Despite the different modeling choices and sample data, our estimates are very similar to those obtained in SW. Similar considerations hold for the parameters of the shock processes, as summarized in Table 2. The standard deviations are not directly comparable to SW, since we allow them to switch over time. But the weighted average of our estimated standard deviations across the two regimes is very similar to the SW estimates. The parameters related to the price-markup shock process are somewhat different, since both the autoregressive parameter ρ_p and the MA parameter μ_p are estimated to be larger than in SW. In this respect our findings are closer to the results of Justiniano and Primiceri (2008),

Table 2—Prior and Posterior Distribution of Shock Processes

		Posterior			
Parameter	Prior	Mode	Mean	5%	95%
Standard deviations in high and low regimes					
σ_a^l	Inv.Gamma (0.1, 2)	0.343	0.352	0.307	0.403
σ_b^l	Inv.Gamma (0.1, 2)	0.158	0.158	0.123	0.194
σ_g^l	Inv.Gamma (0.1, 2)	0.356	0.359	0.303	0.418
σ_I^l	Inv.Gamma (0.1, 2)	0.412	0.415	0.350	0.488
σ_p^l	Inv.Gamma (0.1, 2)	0.146	0.149	0.129	0.173
σ_w^l	Inv.Gamma (0.1, 2)	0.274	0.279	0.243	0.318
σ_m^l	Inv.Gamma (0.1, 2)	0.064	0.066	0.055	0.079
σ_a^h	Inv.Gamma (0.1, 2)	0.643	0.652	0.562	0.759
σ_b^h	Inv.Gamma (0.1, 2)	0.292	0.296	0.228	0.372
σ_g^h	Inv.Gamma (0.1, 2)	0.650	0.660	0.568	0.766
σ_I^h	Inv.Gamma (0.1, 2)	0.569	0.573	0.472	0.689
σ_p^h	Inv.Gamma (0.1, 2)	0.221	0.227	0.194	0.264
σ_w^h	Inv.Gamma (0.1, 2)	0.346	0.355	0.293	0.428
σ_m^h	Inv.Gamma (0.1, 2)	0.315	0.322	0.279	0.378
$diag(P^{vo,l})$	Beta (0.8, 0.16)	0.934	0.916	0.858	0.961
$diag(P^{vo,h})$	Beta (0.8, 0.16)	0.883	0.857	0.759	0.934
MA parameters (μ) and AR parameters (ρ)					
μ_w	Beta (0.5, 0.2)	0.894	0.874	0.789	0.936
μ_p	Beta (0.5, 0.2)	0.986	0.977	0.947	0.995
ρ_{ga}	Beta (0.5, 0.2)	0.425	0.430	0.295	0.567
ρ_a	Beta (0.5, 0.2)	0.999	0.999	0.997	1.000
ρ_b	Beta (0.5, 0.2)	0.447	0.456	0.308	0.617
ρ_g	Beta (0.5, 0.2)	0.940	0.940	0.908	0.968
ρ_I	Beta (0.5, 0.2)	0.769	0.776	0.710	0.841
ρ_p	Beta (0.5, 0.2)	0.947	0.927	0.880	0.958
ρ_w	Beta (0.1, 0.2)	0.996	0.991	0.978	0.999

Notes: The table reports the prior distribution (mean and standard deviation in parentheses) and the estimated posterior mean, mode, and fifth and ninety-fifth percentiles for the parameters describing the shock processes and the diagonal elements of transition matrix for the volatility regimes. The superscripts l and h refer to the low-volatility and high-volatility regimes.

who also find different persistence of price-markup shocks, and ultimately adopt an independently and identically distributed, specification.[25]

In general, and as shown in Figure 1, the contributions of the different shocks to historical fluctuations is consistent with the original SW findings. Markup shocks play a major role in explaining the historical behavior of inflation, while demand-type shocks are the most important drivers of output fluctuations. Additionally, as shown in Appendix D, our model is comparable with the original SW model in fitting the data as measured by the marginal likelihood.

[25] As discussed in Appendix B, when we estimated the posterior mode of the model using an AR(1) specification we found a very low coefficient on the auto-regressive term similar to the i.i.d. setup of Justiniano and Primiceri (2008), while all the other estimates remain very similar to the benchmark case.

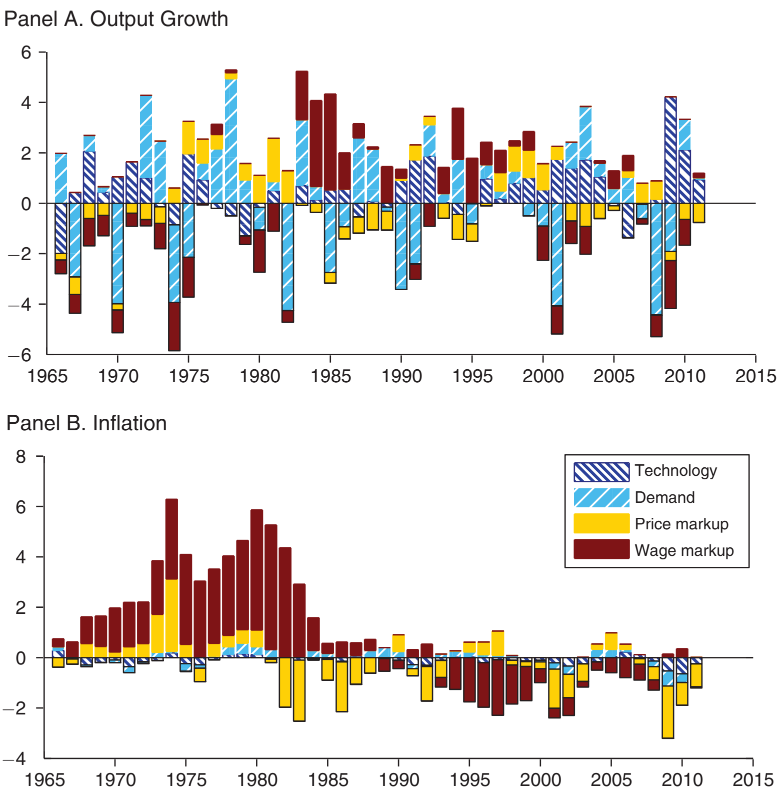

Figure 1. Historical Decomposition

Notes: The figure reports the contribution of different shocks to the historical fluctuations of output growth and inflation. Demand shocks denote the combination of risk-premium, investment-specific, and government expenditure shocks.

Let's now turn our attention to the parameters describing the central bank's behavior, summarized in Table 3. Our estimates for the two weight parameters in the central bank's loss function fall in the estimated range in the literature. Available estimates of the weight tend to be very sensitive with respect to the particular model and data sample. For instance, estimates range from values of $[w_r = 0.005, w_y = 0.002]$ in Favero and Rovelli (2003) to the values of $[w_r = 4.517, w_y = 2.941]$ in Dennis (2006). The posterior mode of our estimates $[w_r = 1.824, w_y = 0.015]$ falls in the middle of this range.[26]

Most interestingly, the last row of Table 3 shows that the posterior mode for the probability of commitment γ equals 0.81. Figure 2, which plots the entire marginal posterior distribution, shows that it is quite precisely estimated. The main implication of our result is that the data clearly rejects both the commonly used setups of commitment $(\gamma = 1)$ and discretion $(\gamma = 0)$. This result is robust to a variety

[26] Allowing for an additional term in the loss function that involves interest rate variability tends to reduce the estimate of w_r, see e.g., Ilbas (2010).

Table 3—Prior and Posterior Distribution of Monetary Policy Parameters

			Posterior			
Parameter		Prior	Mode	Mean	5%	95%
w_y	Output gap weight	Gamma (1.0, 1.0)	0.015	0.017	0.010	0.026
w_r	Interest rate weight	Gamma (1.0, 1.0)	1.824	2.248	1.403	3.288
γ	Probability of commitment	Uniform (0.5, 0.29)	0.811	0.815	0.777	0.851

Note: The table reports the prior distribution (mean and standard deviation in parentheses) and the estimated posterior mean, mode, and fifth and ninety-fifth percentiles for the parameters describing the central bank behavior.

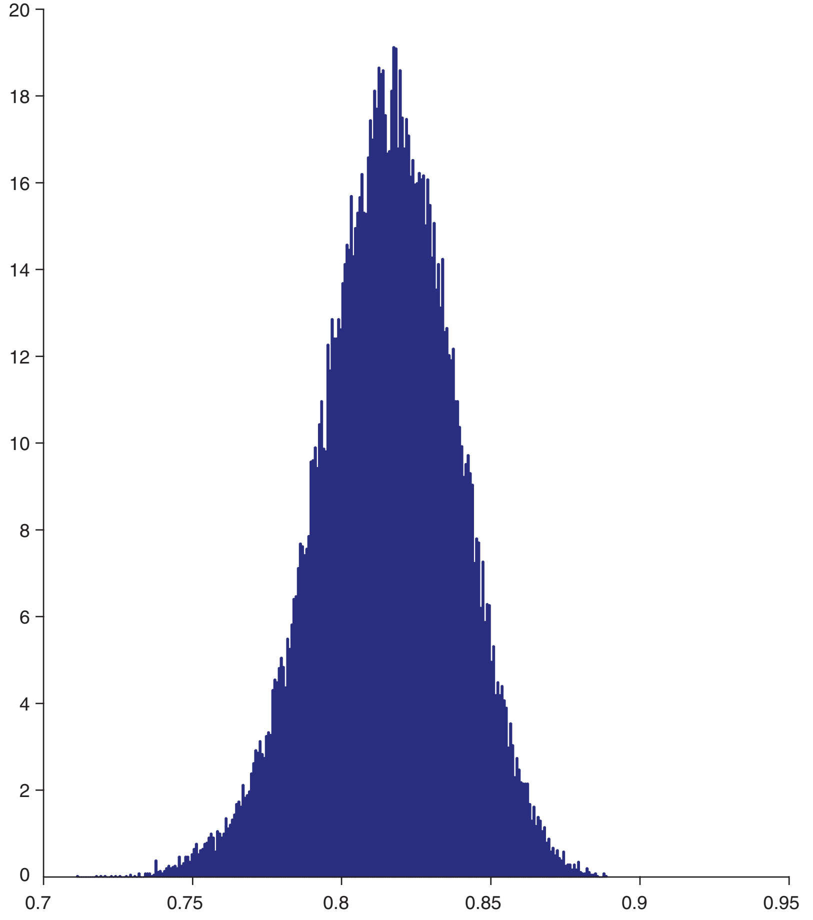

Figure 2. Posterior Distribution of the Probability of Commitment

Note: The figure shows the marginal posterior distribution of γ, the probability of commitment.

of different specifications. As discussed more extensively in Appendix B, we considered different subsamples (using just the pre-financial crisis sample or just the post-Volcker sample) and different measures of the interest rates (e.g., a long-term interest rate).

We also used different priors for γ (Beta prior rather than Uniform) to have an uninformative prior even if credibility is measured according to a different metric. In all the cases considered, the estimated value of γ remains close to 0.8, thus rejecting both commitment and discretion.[27] The same conclusion holds when we separately estimate the alternative commitment settings, and compare the corresponding marginal likelihoods—see Appendix D.

The specific value of γ per se is not indicative of whether the central bank has a high or low level of credibility. On the one hand, a probability of commitment of 81 percent could be viewed as sufficiently close to the ideal commitment case. On the other hand, the use of quarterly data implies that the Federal Reserve is expected to re-optimize on average once every five quarters, arguably a relatively short commitment horizon. Fortunately, counterfactual exercises can shed light on the actual role of commitment in our estimated model, as discussed in the next section.

B. *Counterfactual Analysis*

The main question we address in this section is what would happen under alternative commitment scenarios. To that end we perform counterfactual simulations of the model assuming that the central bank operates either under commitment ($\gamma = 1$) or under discretion ($\gamma = 0$). The remaining parameters of the model are left unchanged.

Table 4 shows how commitment affects the unconditional second moments for some relevant variables. In general, the relative standard deviations and the cross-correlations with output in a model with $\gamma = 0.81$ are closer to the discretion than to the commitment case, and fairly similar to their counterparts in the data.[28] The last line of the table also reports the implied welfare losses with respect to the commitment case, measured in terms of equivalent permanent increase in the inflation rate.[29] According to that measure, the total gains of passing from discretion to commitment are equivalent to a permanent decrease in the inflation rate of 1.2 percent per year. Most of those gains—corresponding to a 1 percent permanent reduction in inflation—could still be achieved if increasing credibility from 0.81 to 1. We can thus conclude that the economy would behave quite differently if the central bank had perfect commitment, and thus there is still some scope to improve credibility.

Next we look at counterfactual paths of inflation and output growth within our sample period under the assumption of discretion and commitment. The structural shocks are fixed at the values estimated under the loose commitment setting (i.e.,

[27] In a paper similar to ours, Chen, Kirsanova, and Leith (2013) conclude that discretion fits the data better than loose commitment. We think there are two main reasons for this difference. First, they estimate a simpler version of the New Keynesian model with three observable variables as opposed to the richer SW model and dataset used here. Second, their preferred specification is discretion with switching in volatility and in the loss function parameters. However, that specification is not directly comparable to one with loose commitment, where due to technical limitations the parameters of the loss function have to be constant.

[28] As an exception, the volatility and cross-correlation of hours is considerably higher than in the data in all the commitment scenarios. The fact that the model does not match these statistics well is not related to our particular way of modeling monetary policy, as the same issue also arises in the original SW model.

[29] Such a measure is often used to gauge losses for the objective functions employed by central banks and is described, for instance, in Jensen (2002).

Table 4—Second Moments and Welfare

	Model			US data
	Commitment	$\gamma = 0.81$	Discretion	1966–2012
Standard deviation (*relative to output*)				
Fed fund rate	0.051	0.085	0.095	0.074
Price inflation	0.035	0.070	0.081	0.049
Wage inflation	0.068	0.095	0.101	0.065
Hours	0.534	0.541	0.540	0.286
Cross-correlations with output				
Fed fund rate	0.052	−0.478	−0.471	−0.571
Price inflation	−0.046	−0.551	−0.637	−0.641
Wage inflation	0.071	−0.319	−0.423	−0.501
Hours	0.397	0.417	0.404	0.102
Welfare loss (permanent change in inflation, percent)	0.000	1.090	1.209	—

Notes: The first three columns report the model unconditional moments of selected variables under alternative commitment settings. Parameters are set at the estimated posterior mode. The last column reports the corresponding values for the US data 1966–2012.

the baseline model). Figure 3 displays these counterfactual paths along with the data. Overall, this exercise further confirms the idea that the dynamics of the macro variables are not easily captured by either discretion or commitment. The data is sometimes closer to commitment, sometimes closer to discretion, and sometimes does not even lie in between the commitment and discretion extremes.

For output growth, both the counterfactuals under commitment and discretion do not display big differences compared to the data. For inflation, in the period from the mid-1970s to the early 1980s, the data is closer to the counterfactual under discretion. Inflation would have been lower under commitment, but not low enough to conclude that the Federal Reserve could have avoided the "Great Inflation" of the 1970s. On the contrary, since the early 1980s the counterfactual path under commitment tracks the inflation data almost perfectly. Under discretion inflation would have been more volatile, especially so in the past decade.

More interestingly, the data do not always lie in between the discretion and commitment cases. For instance, in the early 1980s (the Volcker disinflation period), the interest rate is persistently higher than under commitment and discretion—see the bottom panel. Such a pattern can be rationalized by our loose commitment setting and the intuition is as follows. The possibility that a disinflationary plan is abandoned in the future raises inflation expectations, thus worsening the current policy trade-off. As a result, a central bank that wants to reduce inflation, but is not fully credible, has to set higher interest rates than a central bank with full commitment, at the expense of a deeper recession. The interest rate can also be higher than under discretion. A central bank with loose commitment can make promises to influence future expectations. The promises of high interest rates and low output—conditional on not re-optimizing—lower inflation expectations, thus improving the policy trade-off in earlier periods. On the contrary, a central bank with discretion cannot make any credible promise to improve its policy trade-off. As a result, when a central bank with loose commitment honors its past promises, the interest rate can be higher

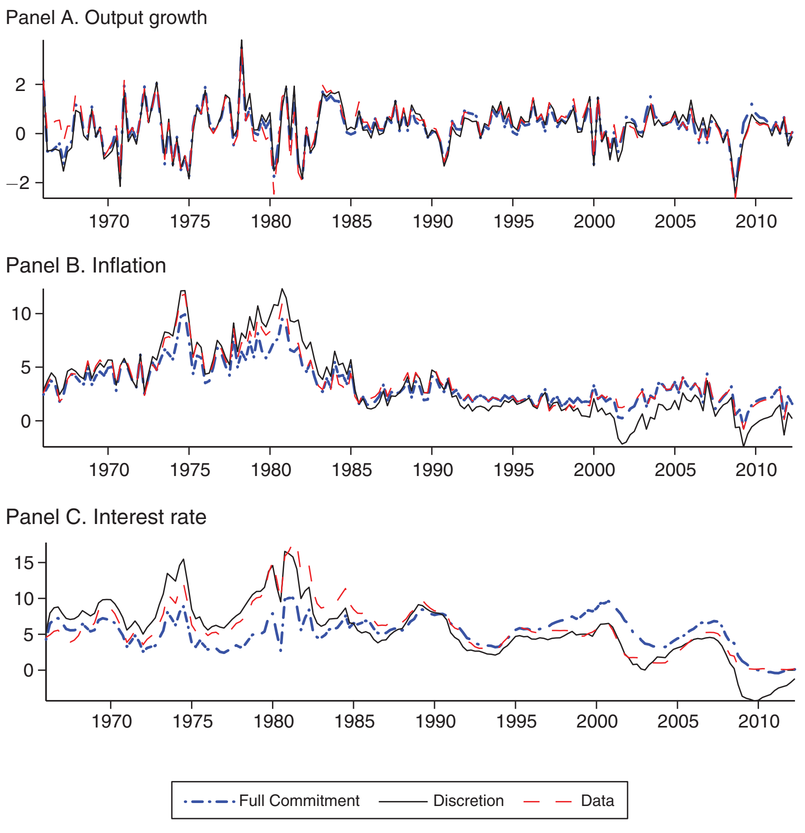

Figure 3. Counterfactual Analysis

Note: The figure reports counterfactual simulations under commitment and discretion, keeping the structural shocks fixed at their estimated values.

than under discretion. As shown in Section IVD, the behavior around the Volcker disinflation is consistent with a scenario of a policy re-optimization occurring after markup shocks. Indeed, as discussed in the next section, a re-optimization episode is likely to have occurred in the early 1980s, when markup shocks were the most important drivers of inflation.

C. *Policy Re-Optimizations Episodes*

In addition to the measure of credibility discussed above, our estimates also give us an indication of specific historical episodes when the Federal Reserve likely abandoned its commitments. This can be done by looking at the evolution of the (smoothed) probabilities of re-optimization, as reported in the top panel of Figure 4. Such smoothed probabilities refer to inference about which regime was prevalent based on using all available information in the sample.

The probability of re-optimization mostly hovers around 0.2 with only a handful of spikes. At a first glance, this may appear inconsistent with our estimated value

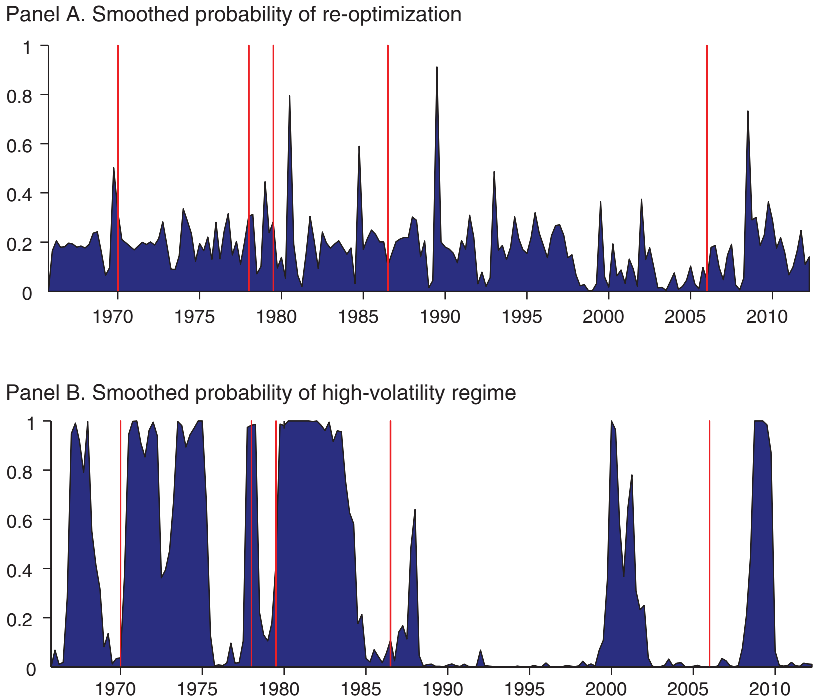

Figure 4. Smoothed Probabilities: Re-Optimization and High-Volatility Regime

Notes: The figure shows the smoothed probability of being in a re-optimization state (upper panel), and of being in the high-volatility regime (lower panel) for the posterior mode estimates. The vertical solid lines indicate the appointment of a new Federal Reserve chairman.

of $\gamma = 0.81$, as one would expect that the probability of re-optimization should be close to 1, 20 percent of the time, and close to zero the remaining 80 percent. However, and as illustrated in Section III, our model identifies re-optimization episodes when there are large differences in the path of variables with or without re-optimizations.[30] When such differences are small, it is nearly impossible to distinguish re-optimizations from continuations of past plans, so that the smoothed probability remains at the unconditional average—i.e., at a level of about 0.2. One possible interpretation of our results is that during prolonged periods with moderate fluctuations, commitment plays a minor role, and it is therefore hard to find evidence in favor or against central bank's deviations from commitment.

We can isolate five dates when re-optimizations were more likely than continuations of previous plans, i.e., the probability of re-optimization exceeds 50 percent. Those dates are (i) 1969:IV, (ii) 1980:III, (iii) 1984:IV, (iv) 1989:III, and (v) 2008:IV. If we lower the cutoff threshold to 40 percent, then we get two additional dates (vi) 1979:I and (vii) 1993:I. A natural test for the validity of our results is to contrast these dates with existing narrative accounts of the US monetary

[30] Additionally, we try to provide some more intuition for this in Appendix C by performing a forecast error decomposition exercise.

policy history. The first two episodes coincide with the appointment of new Federal Reserve Chairmen: Arthur Burns in early 1970 and Paul Volcker in mid-1979. In late 1980 there is another re-optimization, corresponding to a view that there has been a policy reversal during 1980, and that the Volcker policy was credible and effective only from late 1980 or early 1981 (see e.g., Goodfriend and King 2005). We see another re-optimization in 1984 that could potentially correspond to the end of the experiment of targeting non-borrowed reserves that was undertaken in the first few years under Volcker. Only two episodes are identified over the 20-year Greenspan tenure. A first re-optimization occurred in 1989, close to the "Romer and Romer" date of December 1988 (see Romer and Romer 1989). A second re-optimization is identified in 1993. Arguably, this could be related to the major policy change of February 1994 when the Federal Reserve began explicitly releasing its target for the federal funds rate, along with statements of the committee's opinion on the direction of the economy. Those announcements were intended to convey information about future policies, as an additional tool to influence current economic outcomes. The last re-optimization is identified in 2008, at the onset of the financial crisis. That episode could be related to the fact that the zero-lower bound on interest rates became binding and the subsequent adoption of unusual policy measures, like the purchases of mortgage-backed securities and other long-term financial assets.[31] Thus, overall it appears that some of our dates align with changes in Federal Reserve chairmen, while others correspond to changes in operating procedures of the Federal Reserve.

Moreover, there does not seem to be any systematic correspondence between reoptimizations and recessions, or switches in the volatility regime. This can be seen in the bottom panel of Figure 4, showing the smoothed probabilities of being in a high-volatility regime. The identified periods of high volatility are consistent with canonical analyses of US business cycles, but are not aligned with our re-optimization episodes. The 1970s and the early 1980s are characterized by long and recurrent episodes of high volatility. The probability of high volatility surges in correspondence with well-known oil shock episodes: the OPEC oil embargo of 1973–1974, the Iranian revolution of 1978–1979, and the Iran-Iraq war initiated in 1980.[32] From 1984 onward, the economy entered a long period with low volatility—the Great-Moderation—interrupted by the bursting of the dot-com bubble in 2000, and by the events in the aftermath of September 11, 2001. Finally, periods with high volatility are clearly identified in correspondence with the Great Recession and financial crisis of 2008–2009.

There may also be a concern that the switching is actually driven by the state of the economy. We try to address this concern by showing that the observable variables of the model do not help forecast changes in the probability of re-optimization. More specifically, we run Granger causality tests regressing the smoothed probability on four of its lags, and four lags of the seven macro variables. Results are reported in Table 5. The first row labeled "All" considers the restriction that jointly

[31] As discussed in more details in Section IVC, a binding zero lower bound implies a contractionary policy "surprise" that our algorithm captures as a re-optimization. In Appendix B, we show that our results are robust to considering only the precrisis period.

[32] See for example the recent historical survey of Hamilton (2011).

Table 5—Granger Causality Test

	F-statistic	p-value
All	1.3993	0.1038
GDP	1.1258	0.3466
Consumption	0.2326	0.9197
Investment	2.0064	0.0965
Wage	1.4927	0.2072
Hours	0.9282	0.4493
Inflation	0.6068	0.6583
Fed funds	1.1415	0.3393

Notes: The table reports the F-values and p-values of Granger causality tests. The unrestricted regression involves regressing the smoothed probability on four of its lags and four lags of all the seven macro variables, and the restricted regression imposes zeros on the coefficients of those macro variables.

all the observed variables have no forecasting power for the probability of commitment. The p-value shows that we cannot reject this at the 10 percent level. The next rows show the tests of whether individually each of the variables can forecast the probability of re-optimization. At the 10 percent level we fail to reject for all the variables except for investment where the p-value is extremely close to 0.1. These tests suggest that our assumption about exogenous switching appears to be a reasonable one.

D. *What Are the Effects of Policy Re-Optimizations?*

As discussed earlier, the effects of a re-optimization are state-dependent, in the sense that they crucially depend on the history of economic shocks preceding the re-optimization period. Figures 5–7 illustrate this phenomenon showing the impulse responses to technology, government spending, and wage markup shocks. The solid line shows the path under the assumption that a re-optimization never occurs (even though agents expect it to occur with probability $1 - \gamma$). The line with "dots" refers instead to the scenario where a re-optimization occurs after five quarters, but not after that. The difference between the two lines thus measures the effects of a policy re-optimization that occurs in period $t = 5$.

A few interesting observations stand out. For each of the shocks considered, after about six quarters the response of the nominal interest rate does not lie between full commitment (dashed line) and discretion (dash-dotted line). These differences arise because of the uncertainty about future re-optimizations, a feature unique to our loose commitment setting. For example, the interest rate response to a positive wage markup shock, shown in Figure 5, peaks after about ten quarters—as opposed to a much smaller response at a similar horizon under both full commitment and discretion. In turn, the output gap response is deeper and more prolonged, whereas price inflation is close to its counterpart under commitment, and at a much lower level then what would happen under discretion. This is because a central bank with loose commitment, as opposed to one with discretion, is able to influence expectations through promises about future policies. Intuitively, the promise of a deeper and

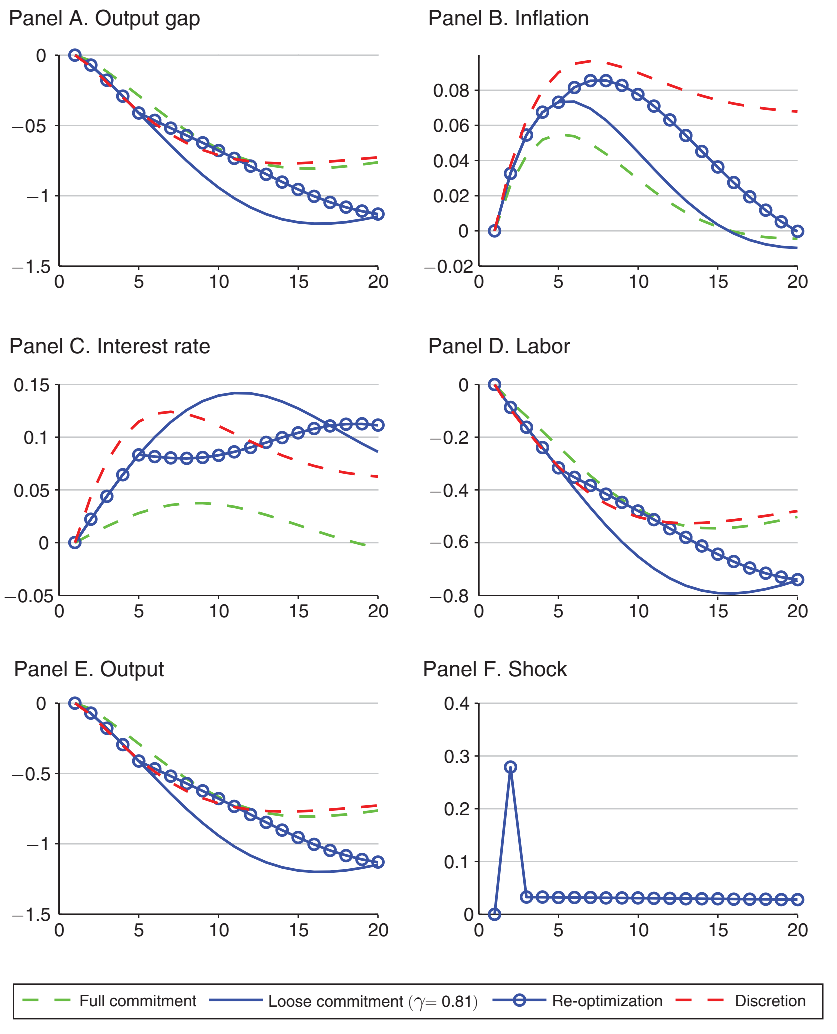

FIGURE 5. IMPULSE RESPONSES TO A WAGE MARKUP SHOCK

Notes: Impulse responses to a 1 standard deviation wage markup shock under alternative commitment settings. The line with "dots" indicates the responses under "loose commitment," assuming that a policy re-optimization occurs after five quarters, and there is no policy re-optimization thereafter.

longer recession dampens inflation expectations and helps achieve higher welfare. A central bank with discretion cannot exploit this channel, and for this reason inflation is high and the output gap is close to the full-commitment level. Clearly, when the central bank re-optimizes, it reneges upon past promises. It then reduces the interest rate, causing inflation to increase and the output gap to become closer to the target.

A similar reasoning also applies to technology and demand shocks. In response to these shocks, the output gap and inflation are well stabilized, and this occurs regardless of the degree of commitment. The effects of policy re-optimizations are thus much smaller. In other words, commitment would not be very important if these shocks were the main sources of business cycle fluctuations. This is consistent with

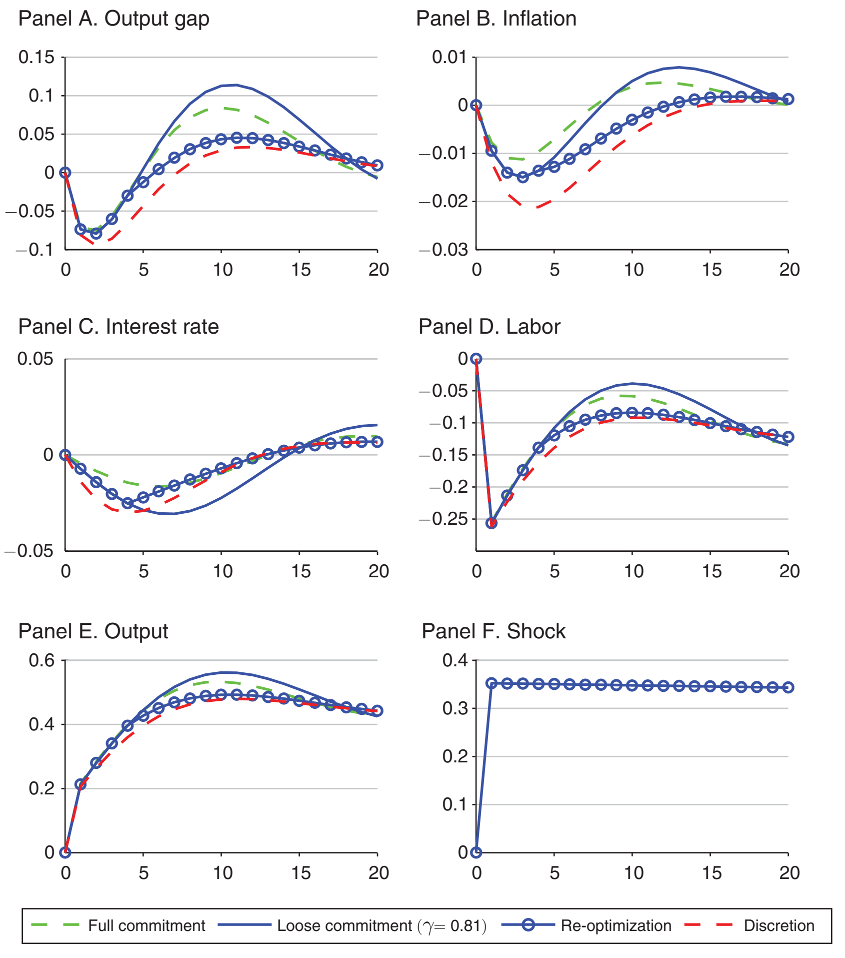

Figure 6. Impulse Responses to a Technology Shock

Notes: Impulse responses to a 1 standard deviation shock under alternative commitment settings. The line with "dots" indicates the responses under "loose commitment," assuming that a policy re-optimization occurs after five quarters, and there is no policy re-optimization thereafter.

what happens in textbook versions of the New Keynesian model, where productivity and demand shocks do not generate any policy trade-offs. Here a trade-off arises because of the presence of several nominal and real frictions, but it is quantitatively small.

Our re-optimizations could also be viewed as a particular class of monetary policy shocks. Within our model, a deviation from previous commitment, like a generic monetary policy shock, constitutes an exogenous and unanticipated change in the course of policy. But there is an important difference between policy re-optimizations and generic monetary shocks. For example, suppose the economy was hit by a sequence of increases in oil prices, and that the Federal Reserve had committed to keep the interest rate high over a certain horizon. In that case, a policy re-optimization would bring about a more expansionary policy than expected. On the contrary, in an economy affected by negative demand shocks, the central bank would commit to

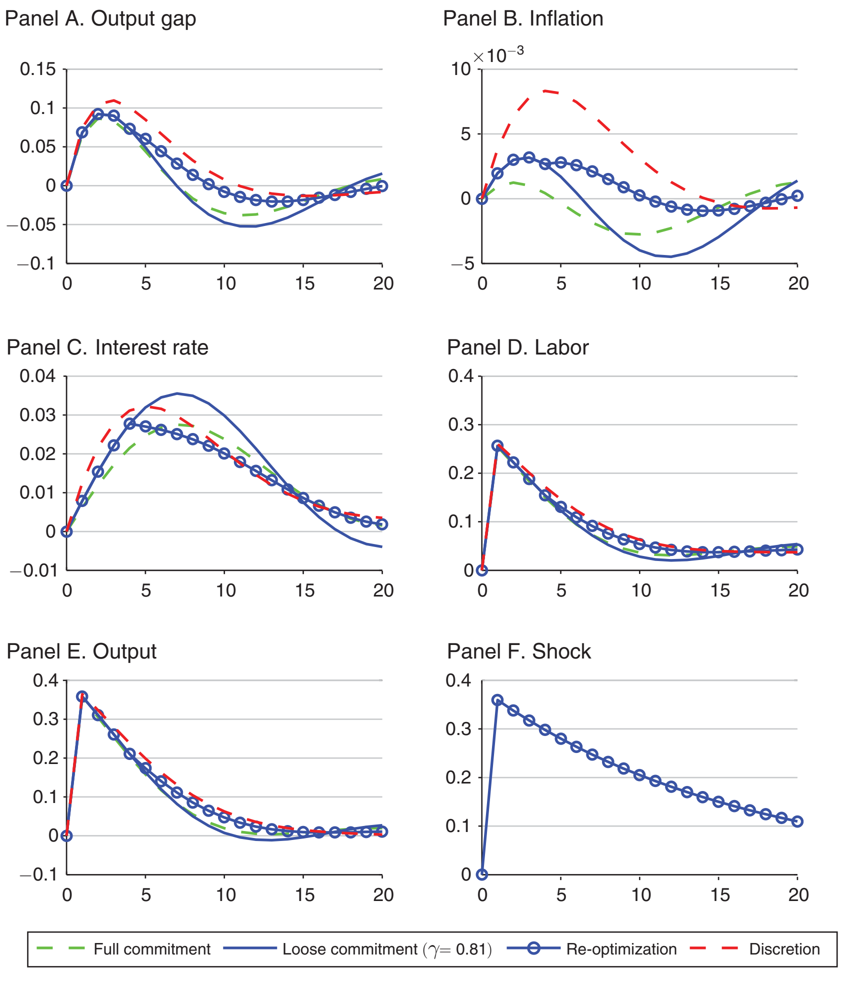

Figure 7. Impulse Responses to a Demand Shock

Notes: Impulse responses to a 1 standard deviation government expenditure shock under alternative commitment settings. The line with "dots" indicates the responses under "loose commitment," assuming that a policy re-optimization occurs after five quarters, and there is no policy re-optimization thereafter.

keep the interest rate low, and a re-optimization would then be associated with an unanticipated contractionary policy. Thus, whether a re-optimization has a positive or a negative effect depends on the entire sequence of shocks previously experienced by the economy.

It then seems useful to analyze the effects of re-optimizations over our sample period. To that end, Figure 8 illustrates the effects of deviating from a promised plan on a given date. Specifically it shows the difference, $[x_t | s_t = 0, x_{t-1}] - [x_t | s_t = 1, x_{t-1}]$ for output growth, inflation, and the nominal interest rate. The thought experiment is the following: if a re-optimization were to occur at each period in our sample, how would the values of output, inflation, and interest rates

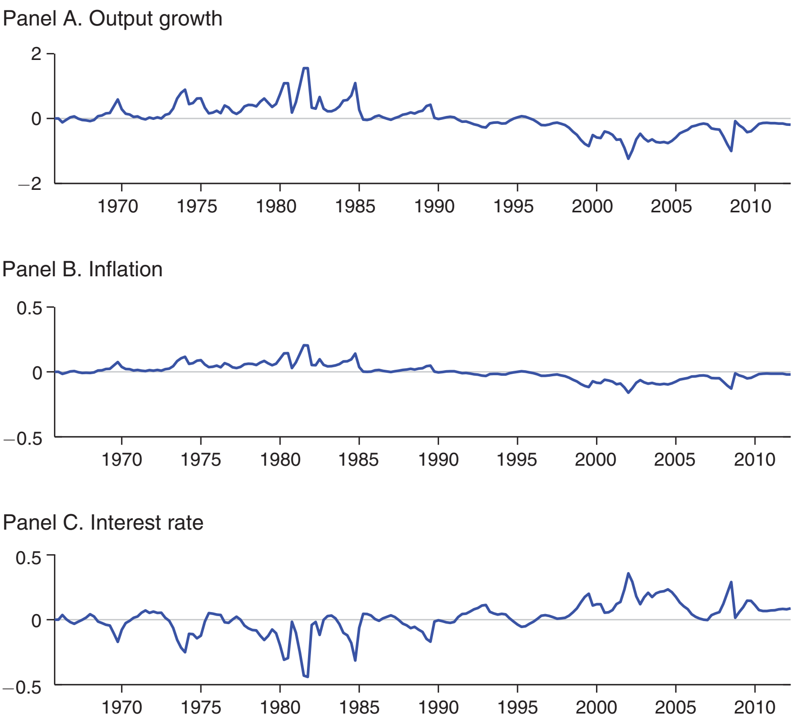

Figure 8. Historical Effects of Policy Re-Optimizations

Notes: The figure shows the effects of re-optimizations over time, measured as the difference between the value conditional on re-optimization and the value conditional on continuation of previous commitment, i.e., $[x_t | s_t = 0, x_{t-1}] - [x_t | s_t = 1, x_{t-1}]$. Vertical lines indicate the episodes where $\Pr(s_t = 0) > 50$ percent.

be different relative to the case where the previous commitment is honored?[33] Policy re-optimizations would have made output and inflation higher until the early 1980s, but would have had a negligible effect (or lowered them) during the Great Moderation. This is because in periods with high volatility the central bank needs to make significant commitments to stabilize the economy with regards to its future actions. These commitments constitute a relevant burden in subsequent periods, and abandoning them would lead to a radically different outcome. Instead, in a low-volatility economy, the central bank carries over less relevant commitments, and there is less need to stabilize the economy. As a consequence, the effects of abandoning past commitments are relatively small.

Regarding the episodes discussed above, Figure 8 shows that the re-optimizations of the 1970s and 1980s are all associated with an increase in the level of inflation and output growth. In other words, those re-optimizations implied a "looser" policy than under the commitment plan. The two re-optimizations of 1993 and 2009 are instead associated with a more contractionary policy. This suggests that Quantitative Easing does constitute a deviation from a commitment plan, but in the sense that

[33] Keep in mind that this exercise is conducted conditioning on the estimated parameters being consistent with an unconditional probability of commitment being equal to our estimated value of 0.81.

monetary policy should have been more expansionary than it actually was. This conforms with the common view that as the economy hit the zero-lower bound, quantitative easing was a necessary but insufficient tool.

V. Conclusion

This paper proposes a structural econometric approach to measure the degree of the Federal Reserve's credibility, within a standard medium-scale macroeconomic model. Monetary policy choices are modeled according to a *loose commitment* setting, where deviations from commitment plans are governed by a regime-switching process.

The conventional approach to think about central banks' credibility is to distinguish between two polar cases: commitment and discretion. Our results depict a very different picture regarding the actual behavior of the Federal Reserve. Over the past four decades, the Fed displayed a certain ability to commit, but its credibility was not perfect. There have been periods where the Fed honored its commitments, but also episodes when it did not. The re-optimization episodes sometimes line up closely with changes of Fed chairmen, and at other times with changes in the operational procedures of the Federal Reserve.

Additionally, it would be misleading to conclude that there has been a one-time change from discretion to commitment. The Federal Reserve has occasionally deviated from its commitment plans throughout the entire sample. If anything, while the deviations in the 1970s implied more expansionary policies, the deviations in the 1990s and 2000s has been more contractionary. In this respect, our results are consistent with earlier studies in the monetary policy literature arguing that the Fed moved from a passive to an active regime.

According to our model, there is still some scope to increase the credibility of the Federal Reserve. Credibility gains would reduce the fluctuations in inflation and economic activity, and thus enhance welfare. Our study, however, remains silent about the specific sources of credibility problems, and on the possible ways to correct them. For instance, imperfect information and model uncertainty may give rise to a trade-off between credibility and flexibility, where occasional deviations from commitment could be desirable. Also, under the helm of chairman Bernanke, the Federal Reserve has taken several measures to better communicate with the public about current and future policy actions. In 2012, the Federal Reserve announced an official inflation target of 2 percent. Additionally it started releasing individual forecasts of the FOMC members' relating to economic activity. Looking forward, our approach could be used to assess the effectiveness of this type of policies.

Appendix A: Loose Commitment versus Regime Switching Interest Rate Rules

This section discusses the relationship between our loose commitment approach and interest rate rules commonly used in the literature. To that end, for the sake of exposition, we apply our approach to a simple New Keynesian model, where neither the structural equations nor the loss function include any backward looking component. In that particular case, the problem of the central bank described by equations (3) and (4) becomes

$$V = \min E \sum_{t=0}^{\infty} (\beta\gamma)^t \Big\{ \frac{1}{2}\big[\pi_t^2 + w_y \tilde{y}_t^2 + w_r r_t{}^2\big] + \beta(1-\gamma)\, V \Big\}$$

$$\text{(A1)} \quad \text{s.t. } \pi_t = \beta E_t\big[\gamma \pi_{t+1} + (1-\gamma)\, \pi_{t+1}^{reop}\big] + \kappa \tilde{y}_t + u_t$$

$$\text{(A2)} \quad \tilde{y}_t = E_t\big[\gamma \tilde{y}_{t+1} + (1-\gamma)\, \tilde{y}_{t+1}^{reop}\big] - \sigma^{-1}\Big\{ r_t - E_t\big[\gamma \pi_{t+1} + (1-\gamma)\, \pi_{t+1}^{reop}\big]\Big\}.$$

The central bank has a period loss function that penalizes fluctuations of inflation (π_t), output gap $(\tilde{y}_t)$, and the nominal interest rate (r_t). The structural relationships between those variables are described by the New Keynesian Phillips curve (A1) and the dynamic IS equation (A2), where the parameters β, σ, and κ indicate the discount factor, the coefficient of risk-aversion, and the slope of the Phillips curve, respectively. As is standard, the cost-push shock (u_t) generates a trade-off between stabilizing inflation and output gap, which is the source of the time-inconsistency problem.

The FOCs to the above problem give

$$\text{(A3)} \quad \pi_t + \lambda_{1,t} - \lambda_{1,t-1} - (\beta\sigma)^{-1} \lambda_{2,t-1} = 0$$

$$\text{(A4)} \quad w_y \tilde{y}_t - \kappa \lambda_{1,t} + \lambda_{2,t} - \beta^{-1} \lambda_{2,t-1} = 0$$

$$\text{(A5)} \quad w_r r_t + \sigma^{-1} \lambda_{2,t} = 0,$$

where $\lambda_{1,t}$ and $\lambda_{2,t}$ are the Lagrange multipliers associated with equations (A1) and (A2), respectively. These conditions can be combined to obtain a targeting rule that fully characterizes the behavior of the central bank (see Giannoni and Woodford 2010). In our case, the targeting rule takes the form of a regime-switching Taylor rule:

$$\text{(A6)} \quad r_t = \phi_{r,s_t} r_{t-1} + \phi_{\Delta r, s_t} \Delta r_{t-1} + \phi_\pi \pi_t + \phi_y \Delta \tilde{y}_t.$$

The coefficients on the values of the interest rate ϕ_{r,s_t} and $\phi_{\Delta r, s_t}$ take the values $\{\phi_{r,1} = 1 + \kappa(\beta\sigma)^{-1}, \phi_{\Delta r,1} = \beta^{-1}\}$ if past plans are continued, and $\{\phi_{r,0} = \phi_{\Delta r,0} = 0\}$ in case of a re-optmizization. On the contrary, the coefficients on inflation $\phi_\pi \equiv \frac{\kappa}{w_r \sigma} > 0$ and output gap growth $\phi_y \equiv \frac{w_y}{w_r \sigma} > 0$ remain constant across the two regimes. In other words, the central bank switches from a Taylor rule with interest rate inertia to one without inertia.

Few additional considerations emerge from the inspection of the targeting rule (A6). First, the parameters of the central bank loss function, w_r and w_y, only affect the coefficients ϕ_π and ϕ_y, while re-optimizations only affect the response to past variables. This exemplifies how policy re-optimizations can be separately identified from changes in other parameters of the model. Second, the parameters of the targeting rule do not depend on the probability of commitment (γ). This clarifies how the source of regime switches is not the change in the probability of commitment, but rather the occasional re-optimizations.

There are some generalizable insights from this simple example. In more general models (with endogenous state variables) the targeting rule displays some inertia with or without re-optimizations, but the degree of inertia during re-optimization episodes is lower. This feature allows us to distinguish policy re-optimizations from other potential sources of regime switches. Also, the parameters of the targeting rule would in general depend on the probability of commitment (γ). As a result, when a central bank re-optimizes it does not operate under discretion (unless $\gamma = 0$). And, when a central bank continues its plans it does not operate under commitment (unless $\gamma = 1$). The fact that the behavior of the central bank cannot be described by commitment or discretion constitutes the main difference of our approached with respect to previous studies (e.g., Matthes 2015).

Appendix B: Robustness Checks

In this section we discuss a variety of robustness checks. Results are summarized in Table B1, where the first column describes how each specification differs from the benchmark case considered in the main text. For practical purposes, the table only reports the posterior mode estimates of the policy parameters w_y, w_r, and γ. The complete results are available upon request to the authors.

To facilitate the comparison, row (a) reports again the benchmark results. Row (b) contains the estimates excluding data since the beginning of the financial crisis, so that the data sample is restricted to end at 2007:II. This is because we want to make sure that our main results are not affected by features of the financial crisis that are not explicitly included in our model, like unconventional policies and the zero-lower bound constraint. The estimates of γ and w_y remain very close to the benchmark case, whereas the estimate of w_r is lower at 0.87. This lower estimate is most likely due to the fact that the Federal Reserve has kept the Fed funds rate constant (around zero) from late 2008 onward. One view advanced by many is that the Federal Reserve has been closer to full commitment since the appointment of Volcker. To test this hypothesis, we estimate our model starting with data from 1979:III. Row (c) shows that γ remains close to 0.8, and we conclude that even under the regimes of Volcker, Greenspan, and Bernanke, the Federal Reserve is not fully committed.[34]

Row (d) shows the estimates under a specification where the Fed Funds rate is replaced with the interest rate on a ten-year Treasury note. This allows us to estimate the model using the entire sample without worrying about the zero lower bound. The resulting estimate of the probability of commitment is 0.8.

We also consider different prior specifications for the monetary policy parameters. Row (e) considers a Beta prior for the probability of commitment γ, with both shape parameters set to 0.5. This prior distribution gives roughly the same weight to values in the $[0.2, 0.8]$ interval, while putting more weight on values near the

[34] We also tried to estimate the model on the 1966:I–1979:II sample, but the MCMC algorithm would not converge. This is not surprising given that we are trying to estimate 42 parameters from 54 data points.

Table B1—Estimates under Various Specifications

	Specification	Posterior mode		
		w_y	w_r	γ
(a)	Benchmark	0.015	1.824	0.811
(b)	1966:I–2007:II sample	0.031	0.874	0.781
(c)	1979:III–2012:II sample	0.013	1.053	0.809
(d)	Ten-year interest rate	0.019	1.244	0.803
(e)	Beta (0.5, 0.5) prior for γ	0.015	1.829	0.812
(f)	Gamma (2, 4) prior for w_r and w_y	0.016	1.950	0.812
(g)	AR (1) price-markup shocks	0.012	2.009	0.729
(h)	$\sigma_l = 0.5$	0.022	0.879	0.801
(i)	$\sigma_l = 1.92$	0.014	1.804	0.812
(j)	$\sigma_l = 3$	0.022	0.879	0.801

Note: The table shows the posterior mode estimates of the loss function weight on output w_y, the loss function weight on interest rate smoothing w_r, and the probability of commitment γ for various specifications.

end points zero and one. Such specification confirms that even with a higher prior probability weight on discretion (0) and commitment (1), the data chooses a value of γ close to 0.8. Row (f) considers Gamma distribution for w_y and w_r with a higher variance. Specifically we use the Gamma distribution with mean 2 and variance 4, but the resulting estimates are very similar to the benchmark case.

We then estimate the model allowing for a different specification of the price-markup process. In the benchmark estimation the price-markup disturbance is modeled as an ARMA(1,1), $\varepsilon_t^p = \rho_p \varepsilon_{t-1} + \eta_t^p - \mu_p \eta_{t-1}^p$. The estimates from Table 2 show that we have an issue of near-cancellation of the roots, and potential weak identification. A similar problem is reported in Justiniano and Primiceri (2008), who end up using an independently and identically distributed specification. To ensure that our estimate of the probability of commitment is not affected by this issue, we consider an additional specification of the price-markup process, where ε_t^p is AR(1). The results are presented in row (g) of Table B1. In this specification the estimate of ρ_p is very close to zero, making this very similar to the independently and identically distributed case of Justiniano and Primiceri (2008). Importantly, the estimates of γ, w_y, and w_r are not affected much by the specification of the price-markup process.

As opposed to the original SW model, in our benchmark estimation we fix the elasticity of labor supply with respect to the real wage, $\sigma_l = 1$. That parameter was not estimated precisely in the SW estimates, and fixing it improves the convergence properties of our estimation algorithm. We then consider three alternative values of σ_l: a value of 0.5, that is close to what is typically estimated in micro studies; a value of 1.92 corresponding to the posterior mode SW; and a value of 3 that is close to the estimates in Bianchi (2013) (who estimates a regime-switching model similar to ours). The estimates of w_y and γ (shown in the last three rows) are very similar to the benchmark case, while the estimate of w_r does change somewhat (see Section IVA for a more in-depth discussion of the sensitivity of this parameter). In conclusion, the estimate of the probability of commitment γ is stable for all the different specifications considered.

Appendix C: Forecast Error Decomposition

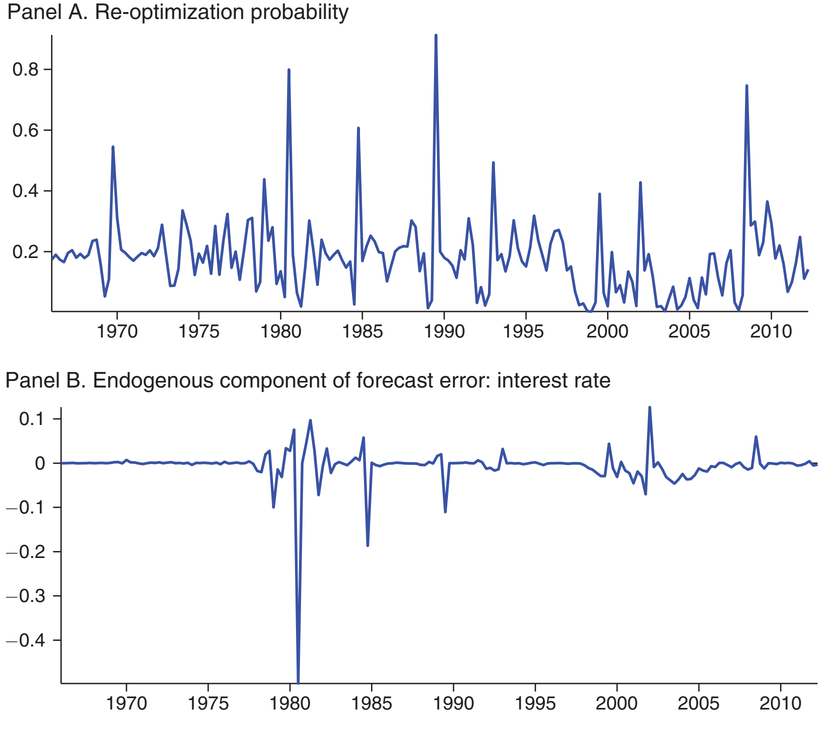

Figure C1. Endogenous Component of Forecast Error and Re-Optimization Probability

Notes: The top panel reports the smoothed probability of being in a re-optimization state. The lower panel shows the component of the forecast error associated with the re-optimization shock. The parameter values used in the calculations are the posterior mode estimates.

In order to better understand the timing of the identified re-optimization episodes, we analyze the forecast error.[35] For the model described in equation (8), the forecast error can be written as

$$\text{(C1)} \qquad \xi_{t+1} - E_t \xi_{t+1} = \mathbf{F}_{s_{t+1}} \xi_t + \mathbf{G} \mathbf{v}_{t+1} - E_t\left[\mathbf{F}_{s_{t+1}} \xi_t\right] - E_t\left[\mathbf{G}\mathbf{v}_{t+1}\right]$$

$$\text{(C2)} \qquad = \mathbf{F}_{s_{t+1}} \xi_t - E_t\left[\mathbf{F}_{s_{t+1}} \xi_t\right] + \mathbf{G}\mathbf{v}_{t+1}.$$

We are interested in the term $\mathbf{F}_{s_{t+1}} \xi_t - E_t\left[\mathbf{F}_{s_{t+1}} \xi_t\right]$, which we will refer to as the "endogenous component" of the forecast error.

This is the part of the forecast error that is due to the re-optimization shock. Note that this term would be zero, if the value of the regime-switching variable s_t (which governs re-optimizations) was perfectly predictable. Figure C1 shows this endogenous component for the interest rate along with the probability of

[35] We thank an anonymous referee for suggesting this exercise.

Table D1—Comparison of Marginal Likelihood

Model	Data sample	Marginal likelihood
Discretion	Full	−1,127.69
Benchmark	Full	−1,020.36
Smets & Wouters (2007)	Prefinancial crisis	−880.25
Benchmark	Prefinancial crisis	−874.45

re-optimization.[36] We can see clearly that the estimation procedure picks out dates where re-optimizations are likely (top panel), which correspond to dates when the endogenous component of the forecast error is large in magnitude (bottom panel).

Appendix D: Comparison of Fit of the Model

Our model nests both the cases of commitment and discretion, thus the estimated results imply that the data gives a higher weight to the posterior at $\gamma = 0.81$ as compared to $\gamma = 0$ or $\gamma = 1$. However, a potentially different way to estimate the model at the end points, $\gamma = 0$ or $\gamma = 1$, is to use an estimation strategy that does not involve regime-switching in the coefficient matrices. What we are worried about is the following. Even though the posterior (and also the likelihood given our diffuse priors) puts a higher weight on $\gamma = 0.81$, once we take into account the estimation uncertainty involved with the regime-switching, is it possible that the fit of the discretion or commitment model can be better than the loose commitment model? To explore this, we separately estimate the commitment and discretion versions of the model using an estimation strategy that does not involve regime-switching in the coefficients. There is still regime switching in the variance of the shocks.

Table D1 shows the marginal likelihoods. These are based on the harmonic mean method of Gelfand and Dey (1994) and the specific one we use is the modified harmonic mean estimator of Geweke (1999). It is reassuring to see that the fit of the loose commitment model is significantly better than the discretion case. With commitment, we had difficulty getting the Bayesian MCMC algorithm to converge. But the posterior mode for commitment is much lower and we are confident that discretion and loose commitment fit the data much better than for commitment. See Givens (2012) among others for supporting evidence that commitment tends to fit the data much worse than discretion.

Finally, we compare our model with the original specification in the SW model to compare the fit. For this exercise the models are estimated stopping the sample before the start of the financial crisis. We use the original priors used in the SW model, and the baseline priors for the loose commitment model. The marginal likelihood for our model is higher but not by much. These marginal likelihood calculations do depend to a small extent on the priors and so we conclude that our model

[36] The figures corresponding to the forecast error decomposition for other variables are almost identical and are omitted for brevity.

fits the data at least as well as the SW model, which is the workhorse model in the literature.

REFERENCES

Adolfson, Malin, Stefan Laséen, Jesper Lindé, and Lars E. O. Svensson. 2011. "Optimal Monetary Policy in an Operational Medium Sized DSGE Model." *Journal of Money, Credit and Banking* 43 (7): 1287–1331.

Backus, David, and John Driffill. 1985. "Inflation and Reputation." *American Economic Review* 75 (3): 530–38.

Barro, Robert J., and David B. Gordon. 1983. "Rules, Discretion, and Reputation in a Model of Monetary Policy." *Journal of Monetary Economics* 12 (1): 101–21.

Barthélemy, Jean, and Magali Marx. 2013. "Monetary Policy Switching and Indeterminacy." Unpublished.

Benigno, Pierpaolo, and Michael Woodford. 2012. "Linear-quadratic approximation of optimal policy problems." *Journal of Economic Theory* 147 (1): 1–42.

Berger, Helge, and Ulrich Woitek. 2005. "Does Conservatism Matter? A Time-Series Approach to Central Bank Behaviour." *Economic Journal* 115 (505): 745–66.

Bianchi, Francesco. 2013. "Regime Switches, Agents' Beliefs, and Post-World War II U.S. Macroeconomic Dynamics." *Review of Economic Studies* 80 (2): 463–90.

Blinder, Alan S. 2000. "Central-Bank Credibility: Why Do We Care? How Do We Build It?" *American Economic Review* 90 (5): 1421–31.

Chappell, Henry W., Thomas M. Havrilesky, and Rob Roy McGregor. 1993. "Partisan Monetary Policies: Presidential Influence through the Power of Appointment." *Quarterly Journal of Economics* 108 (1): 185–218.

Chen, Xiaoshan, Tatiana Kirsanova, and Campbell Leith. 2013. "How Optimal is U.S. Monetary Policy?" Unpublished.

Christiano, Lawrence J., Martin Eichenbaum, and Charles L. Evans. 2005. "Nominal Rigidities and the Dynamic Effects of a Shock to Monetary Policy." *Journal of Political Economy* 113 (1): 1–45.

Clarida, Richard, Jordi Galí, and Mark Gertler. 1999. "The Science of Monetary Policy: A New Keynesian Perspective." *Journal of Economic Literature* 37 (4): 1661–1707.

Cogley, Tim, and Thomas J. Sargent. 2006. "Drifts and Volatilities: Monetary Policies and Outcomes in the Post WWII U.S." *Review of Economic Dynamics* 8 (2): 262–32.

Coibion, Olivier, and Yuriy Gorodnichenko. 2012. "Why Are Target Interest Rate Changes so Persistent?" *American Economic Journal: Macroeconomics* 4 (4): 126–62.

Coroneo, Laura, Valentina Corradi, and Paulo Santos Monteiro. 2013. "Testing for Optimal Monetary Policy via Moment Inequalities." University of York Working Paper 13/07.

Cukierman, Alex. 1992. *Central Bank Strategy, Credibility, and Independence: Theory and Evidence*. Cambridge: MIT Press.

Davig, Troy, and Eric M. Leeper. 2007. "Generalizing the Taylor Principle." *American Economic Review* 97 (3): 607–35.

Debortoli, Davide, Junior Maih, and Ricardo Nunes. 2014. "Loose Commitment in Medium-Scale Macroeconomic Models: Theory and Applications." *Macroeconomic Dynamics* 18 (1): 175–98.

Debortoli, Davide, and Ricardo Nunes. 2010. "Fiscal policy under loose commitment." *Journal of Economic Theory* 145 (3): 1005–32.

Debortoli, Davide, and Ricardo Nunes. 2014. "Monetary Regime Switches and Central Bank Preferences." *Journal of Money, Credit and Banking* 46 (8): 1591–1626.

Dennis, Richard. 2004. "Inferring Policy Objectives from Economic Outcomes." *Oxford Bulletin of Economics and Statistics* 66 (S1): 745–64.

Dennis, Richard. 2006. "The Policy Preferences of the U.S. Federal Reserve." *Journal of Applied Econometrics* 21 (1): 55–77.

Dennis, Richard. 2007. "Optimal Policy in Rational Expectations Models: New Solution Algorithms." *Macroeconomic Dynamics* 11 (1): 31–55.

Erceg, Christopher J., Dale W. Henderson, and Andrew T. Levin. 2000. "Optimal monetary policy with staggered wage and price contracts." *Journal of Monetary Economics* 46 (2): 281–313.

Farmer, Roger E. A., Daniel F. Waggoner, and Tao Zha. 2009. "Understanding Markov-switching rational expectations models." *Journal of Economic Theory* 144 (5): 1849–67.

Favero, Carlo A., and Riccardo Rovelli. 2003. "Macroeconomic Stability and the Preferences of the Fed: A Formal Analysis, 1961–98." *Journal of Money, Credit and Banking* 35 (4): 545–56.

Gelfand, A. E., and D. K. Dey. 1994. "Bayesian Model Choice: Asymptotics and Exact Calculations." *Journal of the Royal Statistical Society* 56 (3): 501–14.

Geweke, John F. 1999. "Using Simulation Methods for Bayesian Econometric Models: Inference, Development, and Communication." *Econometric Reviews* 18 (1): 1–73.

Giannoni, Marc P., and Michael Woodford. 2010. "Optimal Target Criteria for Stabilization Policy." National Bureau of Economic Research (NBER) Working Paper 15757.

Givens, Gregory E. 2012. "Estimating Central Bank Preferences under Commitment and Discretion." *Journal of Money, Credit and Banking* 44 (6): 1033–61.

Goodfriend, Marvin, and Robert King. 2005. "The Incredible Volcker Disinflation." *Journal of Monetary Economics* 52 (5): 981–1015.

Hamilton, James D. 1989. "A New Approach to the Economic Analysis of Nonstationary Time Series and the Business Cycle." *Econometrica* 57 (2): 357–84.

Hamilton, James D. 2011. "Historical Oil Shocks." National Bureau of Economic Research (NBER) Working Paper 16790.

Havrilesky, Thomas. 1995. *The Pressures on American Monetary Policy.* London: Kluwer Academic Publishers.

Ilbas, Pelin. 2010. "Revealing the Preferences of the U.S. Federal Reserve." *Journal of Applied Econometrics* 27 (3): 440–73.

Ireland, Peter N. 1999. "Does the Time-Consistency Problem Explain the Behavior of Inflation in the United States?" *Journal of Monetary Economics* 44 (2): 279–91.

Jensen, Henrik. 2002. "Targeting Nominal Income Growth or Inflation?" *American Economic Review* 92 (4): 928–56.

Justiniano, Alejandro, and Giorgio E. Primiceri. 2008. "The Time-Varying Volatility of Macroeconomic Fluctuations." *American Economic Review* 98 (3): 604–41.

Kara, A. Hakan. 2007. "Monetary Policy under Imperfect Commitment: Reconciling Theory with Evidence." *International Journal of Central Banking* 3 (1): 149–77.

Kim, Chang-Jin, and Charles R. Nelson. 1999. *State-Space Models with Regime Switching: Classical and Gibbs-Sampling Approaches with Applications*. Cambridge: MIT Press.

Kimball, Miles S. 1995. "The Quantitative Analytics of the Basic Neomonetarist Model." *Journal of Money, Credit and Banking* 27 (4, Pt. 2): 1241–77.

Komunjer, Ivana, and Serena Ng. 2011. "Dynamic Identification of Dynamic Stochastic General Equilibrium Models." *Econometrica* 79 (6): 1995–2032.

Kydland, Finn E., and Edward C. Prescott. 1977. "Rules Rather than Discretion: The Inconsistency of Optimal Plans." *Journal of Political Economy* 85 (3): 473–91.

Kydland, Finn E., and Edward C. Prescott. 1980. "Dynamic Optimal Taxation, Rational Expectations and Optimal Control." *Journal of Economic Dynamics and Control* 2 (1): 79–92.

Lakdawala, Aeimit. 2013. "Changes in Federal Reserve Preferences." Unpublished.

Liu, Zheng, Daniel F. Waggoner, and Tao Zha. 2011. "Sources of macroeconomic fluctuations: A regime-switching DSGE approach." *Quantitative Economics* 2 (2): 251–301.

Lohmann, Susanne. 1992. "Optimal Commitment in Monetary Policy: Credibility versus Flexibility." *American Economic Review* 82 (1): 273–86.

Marcet, Albert, and Ramon Marimon. 2011. "Recursive Contracts." http://www.novasbe.unl.pt/images/novasbe/files/file_93_1_1303824140.pdf.

Matthes, Christian. 2015. "Figuring Out the Fed: Beliefs about Policymakers and Gains from Transparency." *Journal of Money, Credit and Banking* 47 (1): 1–29.

Primiceri, Giorgio E. 2005. "Time Varying Structural Vector Autoregressions and Monetary Policy." *Review of Economic Studies* 72 (3): 821–52.

Roberds, William. 1987. "Models of Policy under Stochastic Replanning." *International Economic Review* 28 (3): 731–55.

Romer, Christina D., and David H. Romer. 1989. "Does Monetary Policy Matter? A New Test in the Spirit of Friedman and Schwartz." In *NBER Macroeconomics Annual 1989*, Vol. 4, edited by Olivier J. Blanchard and Stanley Fischer, 121–84. Cambridge: MIT Press.

Rudebusch, Glenn, and Lars E. O. Svensson. 1999. "Policy Rules for Inflation Targeting." In *Monetary Policy Rules*, edited by John B. Taylor, 203–62. Chicago: University of Chicago Press.

Ruge-Murcia, Francisco J. 2003. "Does the Barro-Gordon Model Explain the Behavior of U.S. Inflation? A Reexamination of the Empirical Evidence." *Journal of Monetary Economics* 50 (6): 1375–90.

Salemi, Michael K. 2006. "Econometric Policy Evaluation and Inverse Control." *Journal of Money, Credit and Banking* 38 (7): 1737–64.

Schaumburg, Ernst, and Andrea Tambalotti. 2007. "An Investigation of the Gains from Commitment in Monetary Policy." *Journal of Monetary Economics* 54 (2): 302–24.

Sims, Christopher A. 2002. "Solving Linear Rational Expectations Models." *Computational Economics* 20 (1): 1–20.

Sims, Christopher A., and Tao Zha. 2006. "Were There Regime Switches in US Monetary Policy?" *American Economic Review* 96 (1): 54–81.

Smets, Frank, and Rafael Wouters. 2007. "Shocks and Frictions in US Business Cycles: A Bayesian DSGE Approach." *American Economic Review* 97 (3): 586–606.

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

Söderström, Ulf, Paul Söderlind, and Anders Vredin. 2005. "New-Keynesian Models and Monetary Policy: A Reexamination of the Stylized Facts." *Scandinavian Journal of Economics* 107 (3): 521–46.

Svensson, Lars E. O. 1994. "The Simplest Test of Inflation Target Credibility." Center for Economic and Policy Research (CEPR) Discussion Paper 940.

Svensson, Lars E. O. 1999. "Inflation targeting as a monetary policy rule." *Journal of Monetary Economics* 43 (3): 607–54.

Walsh, Carl E. 1995. "Optimal Contracts for Central Bankers." *American Economic Review* 85 (1): 150–67.

Yun, Tack. 1996. "Nominal Price Rigidity, Money Supply Endogeneity and Business Cycles." *Journal of Monetary Economics* 37 (2): 345–70.