

DISCUSSION PAPER SERIES

No. 4111

OPTIMAL MONETARY POLICY UNDER COMMITMENT WITH A ZERO BOUND ON NOMINAL INTEREST RATES

Klaus Adam and Roberto M Billi

INTERNATIONAL MACROECONOMICS



Centre for Economic Policy Research

www.cepr.org

Available online at:

www.cepr.org/pubs/dps/DP4111.asp

OPTIMAL MONETARY POLICY UNDER COMMITMENT WITH A ZERO BOUND ON NOMINAL INTEREST RATES

Klaus Adam, University of Frankfurt and CEPR
Roberto M Billi, University of Frankfurt

Discussion Paper No. 4111
November 2003

Centre for Economic Policy Research
90–98 Goswell Rd, London EC1V 7RR, UK
Tel: (44 20) 7878 2900, Fax: (44 20) 7878 2999
Email: cepr@cepr.org, Website: www.cepr.org

This Discussion Paper is issued under the auspices of the Centre's research programme in **INTERNATIONAL MACROECONOMICS**. Any opinions expressed here are those of the author(s) and not those of the Centre for Economic Policy Research. Research disseminated by CEPR may include views on policy, but the Centre itself takes no institutional policy positions.

The Centre for Economic Policy Research was established in 1983 as a private educational charity, to promote independent analysis and public discussion of open economies and the relations among them. It is pluralist and non-partisan, bringing economic research to bear on the analysis of medium- and long-run policy questions. Institutional (core) finance for the Centre has been provided through major grants from the Economic and Social Research Council, under which an ESRC Resource Centre operates within CEPR; the Esmée Fairbairn Charitable Trust; and the Bank of England. These organizations do not give prior review to the Centre's publications, nor do they necessarily endorse the views expressed therein.

These Discussion Papers often represent preliminary or incomplete work, circulated to encourage discussion and comment. Citation and use of such a paper should take account of its provisional character.

Copyright: Klaus Adam and Roberto M Billi

ABSTRACT

Optimal Monetary Policy Under Commitment with a Zero Bound on Nominal Interest Rates*

We compute the optimal non-linear interest rate policy under commitment for a forward-looking stochastic model with monopolistic competition and sticky prices when nominal interest rates are bounded below by zero. When the lower bound binds, the optimal policy is to reduce the real rate by generating inflation expectations. This is achieved by committing to increase future interest rates by less than what purely forward-looking policy would suggest. As a result, there is a ‘commitment bias’, i.e., average output and inflation turn out to be higher than their target values. Calibrating the model to the US economy we find that the quantitative importance of the average effects on output and inflation are negligible. Moreover, the empirical magnitude of US mark-up shocks is too small to entail zero nominal interest rates. Real rate shocks, however, plausibly lead to a binding lower bound under optimal policy, albeit relatively infrequently. Interestingly, the presence of binding real rate shocks alters the optimal policy response to (non-binding) mark-up shocks.

JEL Classification: C63, E31 and E52

Keywords: commitment, liquidity trap, new Keynesian, non-linear optimal policy and zero interest rate bound

Klaus Adam
Department of Economics
University of Frankfurt
Mertonstr. 17, PF 64
60054 Frankfurt
GERMANY
Tel: (49 69) 798 25282
Fax: (49 69) 798 25272
Email: kadam@wiwi.uni-frankfurt.de

For further Discussion Papers by this author see:
www.cepr.org/pubs/new-dps/dplist.asp?authorid=151268

Roberto M Billi
Department of Economics
University of Frankfurt
Mertonstr. 17, PF 64
60054 Frankfurt
GERMANY
Tel: (49 69) 798 25283
Email: billi@wiwi.uni-frankfurt.de

For further Discussion Papers by this author see:
www.cepr.org/pubs/new-dps/dplist.asp?authorid=159764

* Thanks go to Joachim Keller, Albert Marcet, Ramon Marimon, Athanasios Orphanides, Volker Wieland, and Mike Woodford for helpful comments and discussions. Errors remain ours. This Paper is produced as part of a CEPR research network on 'The Analysis of International Capital Markets: Understanding Europe's Role in the Global Economy', funded by the European Commission under the Research Training Network Programme (Contract No: HPRN-CT-1999-00067).

Submitted 30 September 2003

1 Introduction

This paper studies optimal monetary policy when taking into account that nominal interest rates cannot be set to negative values.¹ The policy implications of the lower bound on nominal interest rates have recently received considerable attention since nominal interest rates in major world economies are either already at or getting closer to zero.

A situation with nominal interest rates close to zero is generally deemed problematic as the inability to further lower nominal rates can lead to higher than desired real interest rates. In particular, when agents hold deflationary expectations the economy might embark on a deflationary equilibrium path, sometimes referred to as a ‘liquidity trap’, where high real interest rates generate demand shortfalls and thereby fulfill the expectations of falling prices.

We consider optimal monetary policy under commitment in a micro-founded model with monopolistic competition and sticky prices in the product market (see Clarida, Galí and Gertler (1999) and Woodford (2003)). Although the model we employ has been widely used to study optimal monetary policy and short-run fluctuations, to our knowledge we are the first to determine the optimal nonlinear interest rate rules and the associated full stochastic rational expectations equilibrium when taking into account the zero lower bound. The determination of the stochastic equilibrium allows us to calibrate the model to the U.S. economy and to assess the *quantitative* importance of the zero lower bound for the U.S. economy.

To preview our results, first, the zero lower bound appears inessential when dealing with mark-up shocks (shocks to the model’s aggregate supply equation). More precisely, the empirical magnitude of mark-up shocks observed during the period 1983-2002 in the U.S. is not sufficient for the zero-lower bound to become binding. This remains the case even if the true variance of mark-up shocks were tenfold above our estimated value.

Second, while shocks to the natural real rate of interest (shocks to the model’s aggregate demand equation) may cause the lower bound to become binding, this happens relatively infrequently and is a feature of optimal

¹In principle negative nominal rates are feasible, e.g., if one is willing to give up free convertability of deposits and other financial assets into cash or if one could levy a tax on money holdings. However, these measures are generally not considered to be feasible policy options.

policy. Based on our estimates for the 1983-2002 period, the bound would be expected to bind under optimal policy only in one quarter every 28 years.² Moreover, once zero nominal interest rates are observed they can be expected to endure for not more than 1 to 2 quarters on average. Clearly, these results are sensitive to the standard deviation of the estimated real rate process. In particular, we find that zero nominal rates would occur much more frequently if the real rate process had a somewhat larger variance.

Third, optimal policy reacts to a binding zero lower bound on nominal interest rates by creating inflationary expectations in the form of a commitment to let future output gaps and inflation rates increase above zero. The policymaker thereby effectively lowers the real interest rates that agents are confronted with. Since reducing real rates using inflation is costly (in welfare terms), the policymaker has to trade-off the losses generated by too high real rates with those generated by too high inflation rates.

To illustrate the optimal policy response to a binding real rate shock in the U.S., consider the optimal policy reaction to a negative 3 standard deviation shock of the real rate.³ Nominal interest rates will result equal to zero for at least 2 quarters and only slowly return to their average level of about 3.5%. Similarly, inflation is allowed to increase to about 0.6% annually for more than 2 years and output, which is initially negative, is allowed to overshoot its potential by roughly 0.5% in the subsequent 2 years.

Forth, while the optimal policy response to shocks is to generate a ‘commitment bias’ by promising above average output and inflation, when calibrating the model to the U.S. economy the quantitative effects for average output and inflation turn out to be negligible. Thus, under optimal policy we should observe zero average inflation and zero average output gaps in the U.S..⁴ Even if increasing the variance of the mark-up and real rate shocks tenfold, average annual inflation would rise to only about +1% and the average output gap to roughly +0.1%.

Finally, we find that the presence of binding negative real rate shocks alters the optimal response to non-binding shocks. This surprising feature

² Clearly, under sub-optimal policy this might happen more or less often.

³ Our baseline calibration implies that the annual real rate is then (temporarily) negative and approximately equal to -1.48%.

⁴ Zero inflation is optimal because it minimizes the price dispersion between firms with sticky prices and we abstract from the money demand distortions associated with positive nominal interest rates.

emerges because the policymaker has to fulfill a neutrality constraint implying that monetary policy cannot affect the average real interest rate in any stationary equilibrium. The inability to lower nominal rates as much as desired in response to negative real rate shocks induces the policymaker to choose lower real rates in response to all other shocks (positive real rate shocks, positive and negative mark-up shocks). In this sense locally binding shocks can have global implications for the optimal policy reaction under commitment.

The remainder of this paper is structured as follows. Section 2 briefly discusses the related literature. Section 3 introduces the monopolistic competition model with sticky prices together with a welfare-based objective function. In section 4 we demonstrate the model's ability to generate low output levels and low inflation rates in the presence of zero nominal interest rates by characterizing the complete set of rational expectations equilibria. In section 5 we present our calibration of the model and illustrate how the shock processes for the U.S. economy were identified. Section 6 discusses the solution method we used to solve for the optimal nonlinear policy functions and presents the optimal policy for the calibrated version of the model; we also discuss the robustness of our results to various changes in the calibration. Section 7 briefly summarizes the main conclusions.

2 Related Literature

A number of recent papers study the implications of the zero lower bound on nominal interest rates for optimal monetary policy.

Eggertsson and Woodford (2003) derive analytically optimal targeting rules under commitment for a sticky price economy with monopolistic competition; but they do not solve for the full rational expectations equilibrium. This paper solves numerically for the dynamic stochastic general equilibrium expressing output, inflation, and optimal interest rates as functions of the state of the economy. This allows us to calibrate the model to the U.S. economy and study the quantitative implication of the zero lower bound.

A related set of papers focused on optimal monetary policy under discretion. Eggertsson (2003) shows that discretionary policy displays a deflation bias and analyzes the role of nominal debt policy as a way to achieve commitment. Adam and Billi (2003) derive the optimal nonlinear discretionary

policy for a New Keynesian model and the associated stochastic rational expectations equilibrium when calibrating the model to the U.S. economy.

The performance of simple monetary policy rules has been analyzed by Fuhrer and Madigan (1997), Orphanides and Wieland (1998), and Wolman (2003). A main finding of these contributions is that policy rules formulated in terms of inflation rates, e.g., Taylor rules, can generate significant real distortions when the targeted inflation rate is close enough to zero. Reifschneider and Williams (2000) and Wolman (2003) show that simple policy rules formulated in terms of a price level target can significantly reduce the real distortions associated with the zero lower bound on interest rates. Benhabib et al. (2002) studied the global properties of Taylor-type rules showing that these might lead to self-fulfilling deflations that converge to a low inflation or deflationary steady state. Evans and Honkapohja (2003) studied the properties of global Taylor rules under adaptive learning showing the existence of an additional steady state with even lower inflation rates.

The role of the exchange rate and monetary base rules in overcoming the adverse affects of a binding lower bound on interest rates has been analyzed, for example, by Svensson (2003), Coenen and Wieland (2003), and McCallum (2003).⁵

3 The Model

We consider the linearized equilibrium equations of a small monetary policy model based on a representative consumer and firms operating in monopolistic competition facing restrictions on the frequency of price adjustments (Calvo (1983)). The model is often referred to as the ‘New Keynesian’ model and has frequently been studied in the literature, e.g. Clarida, Galí and Gertler (1999) and Woodford (2003).

The behavior of the private sector is described by two equations. On the one hand, profit maximizing price setting behavior by firms implies an ‘aggregate supply’ (AS) equation of the form

$$\pi_t = \beta E_t \pi_{t+1} + \lambda y_t + u_t \quad (1)$$

⁵Further articles dealing with the relevance of the zero lower bound can be found in the special issues of the Journal of Japanese and International Economies Vol 14, 2000 and the Journal of Money Credit and Banking Vol 23, No.3 Part 2, 1991.

where π_t denotes the inflation rate from period $t-1$ to t and y_t the deviation of output from its natural rate.⁶ The shock u_t denotes inefficient variations in the natural rate of output, due for example to changes in the mark-up charged by firms, and may be interpreted as a supply shock. The parameter $\beta \in (0, 1)$ is the discount factor and $\lambda > 0$ indicates how sensitive inflation reacts to deviations of output from its natural rate. On the other hand, the Euler equation describing households' optimal labor and consumption decisions delivers an 'IS curve' of the form

$$y_t = E_t y_{t+1} - \varphi(i_t - E_t \pi_{t+1}) + g_t \quad (2)$$

where i_t denotes the nominal interest rate (in terms of deviations from the interest rate consistent with the zero inflation steady state). And g_t is a shock to the Wicksellian natural rate of interest with unconditional mean equal to zero

$$g_t = \varphi(r_t - r^*) \quad (3)$$

where r_t is the real rate consistent with the flexible price equilibrium and $r^* = 1/\beta - 1$ is the real rate of the deterministic zero inflation steady state. The shock g_t may be interpreted as being due to preference shocks thus constitutes a demand shock. Note that taking unconditional expectations in equation (2) it follows that in a stationary rational expectations equilibrium the average real interest rate is equal to r^* , therefore, independent of monetary policy. This feature turns out to be important in the latter part of the paper.

We suppose that the policymaker freely controls the short-term nominal interest rate i_t but control is subject to a lower bound emerging from the presence of money that offers a zero nominal return. This implies that nominal interest rates must be non-negative, which in terms of our notation is captured by the restriction

$$i_t \geq -r^*. \quad (4)$$

We assume that the interest rate is the only available policy instrument and deliberately abstract from a number of alternative policy channels, most notably fiscal policy and possibly exchange rate and quantity-based monetary policies. Although these additional policy instruments may potentially

⁶The natural rate of output is the output level that would emerge if prices were flexible.

be important to ameliorate the effects of a zero bound on nominal interest rates, focusing on interest rate policy in isolation is nevertheless of considerable interest: knowing what interest rate policy alone can achieve in avoiding liquidity traps allows to assess whether there is any need for employing other policy instruments at all. This is important, given that the policy instruments other than nominal interest rates are often subject to (potentially uncertain) political approval by external authorities and may therefore not be readily available to the policymaker.

Moreover, the omission of exchange rate policies and direct money policies may be less severe than one might initially think. Clarida, Galí and Gertler (2001) have shown that one can reinterpret the present model as an open economy model where there exists a one-to-one correspondence between interest rate policies and exchange rate policies. It is then inessential whether policy is formulated in terms of interest rates or exchange rates. In addition, Eggertsson and Woodford (2003) have shown that monetary policies in the form of open market operations during periods with zero nominal interest rates have no effect on the rational expectations equilibria of the present model, unless they influence the future interest rate policy. When nominal interest rates are larger than zero, there is again a one-to-one correspondence between interest rate policy and direct money policies, which shows that the restriction to interest rate policies alone is again less severe than it might initially appear.

As shown in Woodford (2001), the welfare of the representative agent can be approximated by a quadratic function in output and inflation

$$W_t = -E_t \left[\sum_{i=0}^{\infty} \beta^i (\pi_{t+i}^2 + \alpha y_{t+i}^2) \right] \quad (5)$$

where the weight $\alpha > 0$ depends on the underlying preference and technology parameters.

Intuitively, the welfare function captures the following two effects. First, output gaps are costly because they denote deviations of output from the (approximately efficient) natural rate of output. Second, inflation is costly because it generates price dispersion between firms that cannot perfectly adjust prices and thereby induces socially inefficient substitution between the goods produced by different entrepreneurs.⁷

⁷ Substitution is socially inefficient because firms face increasing marginal costs of production.

Importantly, the welfare function does not contain any element capturing the distortionary effects of positive nominal interest rates, an issue that has been emphasized by Milton Friedman. The objective function, thus, implicitly assumes that real money balances are of negligible importance (in utility terms) and that the distortion generated by positive nominal interest rates can be abstracted from. One may interpret this in the sense of a cash-less limit economy, as in Woodford (1998). Moreover, we note that the neglect of money balances does not seem to entail any significant approximation error. Schmitt-Grohé and Uribe (2001), for example, find that price level stability should indeed be the overriding policy objective in the presence of sticky prices, even when properly taking into account the distortions generated by positive nominal interest rates.

Given the aforementioned setup, we assume that the monetary authority maximizes the objective (5) subject to the forward-looking AS-equation (1) and IS-equation (2), the zero lower bound on nominal interest rates (4), and the law of motion for the shocks, given by

$$u_t = \rho_u u_{t-1} + \varepsilon_{u,t} \quad (6)$$

$$g_t = \rho_g g_{t-1} + \varepsilon_{g,t} \quad (7)$$

with $|\rho_i| < 1$ and $\varepsilon_{i,t} \sim iid(0, \sigma_i^2)$ for $i = u, g$.

If one abstracts from the presence of the zero lower bound (4), the policy problem is a standard linear quadratic control problem as considered by Clarida et al. (1999) or Woodford (2001). The presence of the lower bound, however, renders the policy problem nonlinear, since the constraint (4) causes linear policies to be unfeasible.

4 Zero Bound and Liquidity Traps

In this section we assess the suitability of the simple model described in the previous section for studying issues related to the zero lower bound and ‘liquidity traps’.

We believe that a minimum requirement of any model used to analyze these issues is that it should be able to replicate the Japanese experience of the 1990s, i.e., low nominal interest rates, deflation, and negative output gaps. It is precisely the apparent existence of such unfavorable ‘liquidity trap equilibria’ that causes the zero lower bound to be of economic interest.

We determine the complete set of Rational Expectations Equilibria (REE) when $i_t \equiv -r^*$, i.e., when nominal interest rates are at their lower bound. We then determine whether there exist REE that display properties associated with a liquidity trap, as defined above. In appendix 8.1 the following result is derived:

Proposition 1 Suppose $i_t = -r^*$ for all t . The full set of Rational Expectations Equilibria for the model described by equations (1) and (2) is given by

- a continuum of locally explosive solutions, possibly involving sunspots, where either $(y_t, \pi_t) \rightarrow (+\infty, -\infty)$ or $(y_t, \pi_t) \rightarrow (-\infty, +\infty)$, and
- a set of stationary solutions

$$\begin{pmatrix} \pi_t \\ y_t \end{pmatrix} = \begin{pmatrix} -r^* \\ -\frac{1-\beta}{\lambda}r^* \end{pmatrix} + \Gamma \begin{pmatrix} u_t \\ g_t \end{pmatrix} + \sum_{n=0}^{\infty} \phi^n \begin{pmatrix} \omega \\ 1 \end{pmatrix} s_{t-n} \quad (8)$$

where

$$\Gamma = \begin{pmatrix} \frac{-1+\rho_u}{\rho_u\varphi\lambda+\rho_u-1+\rho_u\beta-\rho_u^2\beta} & \frac{-\lambda}{-1+\rho_g+\rho_g\varphi\lambda+\rho_g\beta-\rho_g^2\beta} \\ \frac{-\rho_u\varphi}{\rho_u\varphi\lambda+\rho_u-1+\rho_u\beta-\rho_u^2\beta} & \frac{-1+\rho_g\beta}{-1+\rho_g+\rho_g\varphi\lambda+\rho_g\beta-\rho_g^2\beta} \end{pmatrix} \quad (9)$$

and the sunspot variable $s_t \in R^1$ is an arbitrary martingale difference series, $\phi \in (0, 1)$, and $\omega > 0$.

Clearly, the explosive solutions mentioned in proposition 1 seem inadequate explanations of liquidity traps, as either inflation or output are increasing without bound.⁸ Moreover, such equilibria are Pareto dominated by the stationary equilibria since the rate of growth of output or inflation is (locally) larger than $1/\beta$, see appendix 8.1.

The situation differs for the stationary solutions (8). Since the coefficients in the respective columns of Γ have the same sign, mark-up shocks and demand shocks can create both low output and low inflation when interest rates are at their lower bound. Clearly, similar phenomena may be generated by sunspot shocks since $\omega > 0$. Solutions of the form (8), thus, have the potential to replicate the Japanese experience of the recent years.

⁸Since we use a linearized model, these variables need not increase without bound also in the underlying nonlinear model. Nevertheless, these explosive solutions seem unattractive as they would still imply either high inflation or high output for the underlying nonlinear model.

In the remaining part of the paper we will focus on stationary fundamental equilibria. One reason for doing so is that commitment solutions implicitly select between the set of rational expectations equilibria and thereby automatically reject Pareto dominated equilibria, which in the present case are the explosive equilibria and any equilibria involving sunspots. Focusing on stationary solution seems further justified by the fact that the non-stationary solutions clearly fail to generate equilibrium paths resembling liquidity traps. Moreover, since the stationary fundamental solution is locally isolated among the set of fundamental rational expectations solutions, learning dynamics may be expected to select the stationary solution instead of the explosive solutions, as in the analysis of Evans and Honkapohja (2003) with a related model.

As a final remark, we should mention that the model is globally stable in the sense that there always exist feasible interest rate policies that are consistent with a stationary equilibrium path. This differs from earlier work, e.g., Orphanides and Wieland (2000), where for some realizations of the shocks the economy possess only destabilizing equilibria. The global stability property of the present model, however, might be sensitive to the introduction of lagged inflation terms in the price setting equation (1), a feature that would have to be explored in future work.

5 Model Calibration

Since we seek to asses the quantitative importance of the zero lower bound for interest rate policy we have to choose parameter values to calibrate the model. In particular, we need values for the IS and AS parameters β , λ , and φ , the welfare weight α , and the shock parameters ρ_i and σ_i ($i = u, g$). We employ the values of Woodford (1999), i.e.,

$$\begin{aligned}\lambda &= 0.024 \\ \varphi &= 6.25 \\ \alpha &= 0.048\end{aligned}$$

which in turn are based on estimates in Rotemberg and Woodford (1998) for the U.S. economy (1980:1-1995:2).

Given these parameter values we use the methodology of Rotemberg and Woodford (1998) to identify the shock processes. We look at quarterly U.S. data from 1983:1-2002:4, where the starting point is motivated by the end

of the disinflation policy under Federal Reserve chairman Paul Volcker, see Clarida et al. (2000). During this sample period monetary policy can be assumed reasonably stable, which is essential for the identification of the shocks that follows.

Output is measured by linearly detrended log real GDP, and inflation is taken as the log quarterly difference of the implicit deflator.⁹ All variables are expressed in percentage terms. Detrended output is depicted in figure 1.

For the interest rate we use the quarterly average of the fed funds rate in deviation from the average real rate for the whole sample, which is approximately equal to 3.5% (in annual terms).¹⁰ Based on the latter we can set the quarterly discount factor equal to $\beta = 0.99125$. To make interest rates and inflation rates consistent, we define both in terms of quarterly rates. The graphs in the latter part of the paper, however, will report annual rates to improve readability.

To identify the shock processes in equations (1) and (2) we first have to construct expectations. Following Rotemberg and Woodford (1998) we use the predictions from an unconstrained VAR in output, inflation, and the fed funds rate with three lags.¹¹ The VAR describes the data rather well and the correlations of the VAR residuals, depicted in figure 2, do not display significant remaining correlations. Using the VAR predictions to substitute expectations in equations (1) and (2) one can then identify the shocks u_t and g_t . The implied shock series are shown in figure 3.

Fitting a univariate AR(1) process to these shocks delivers the following parameter values

$$\begin{aligned}\rho_u &= 0.14446 \quad (0.1128) \\ \rho_g &= 0.91283 \quad (0.0505) \\ \sigma_u &= 0.15 \\ \sigma_g &= 1.06\end{aligned}$$

where numbers in brackets indicate the standard deviations of the point estimates.¹² As in Ireland (2002) and Rotemberg and Woodford (1998),

⁹The data is taken from table 7.1 Bureau of Economic Analysis: www.bea.gov.

¹⁰We implicitly assume that the positive inflation rates displayed in the sample did not affect the real rate such that the nominal interest rate in the zero inflation steady state is equal to this real rate.

¹¹This lag length is suggested by the Akaike information criterion when allowing for up to 8 lags and coincides with the lag length used by Rotemberg and Woodford (1998).

¹²The univariate AR(1) processes describe the shock process u_t and g_t quite well and

real rate shocks are highly persistent. The mark-up shocks, however, do not display any significant autocorrelation.¹³ The estimates imply that the annual standard deviation of the mark-up shock is 0.61%. Similarly, the annual standard deviation of the real rate, as implicitly defined in equation (3), is equal to 1.66%.¹⁴

6 Optimal Policy with Zero Bound

6.1 Model Solution

Due to the presence of the zero lower bound analytical results for optimal interest rate policy are unavailable. For this reason we have to rely on numerical methods to determine the optimal nonlinear commitment policies.

An important complication that arises, however, is that the policymaker's maximization problem

$$\begin{aligned} & \max -E_0 \left[\sum_{t=0}^{\infty} \beta^t (-\pi_t^2 - \alpha y_t^2) \right] \\ & \text{s.t.:} \\ & \pi_t = \beta E_t \pi_{t+1} + \lambda y_t + u_t \quad (10a) \\ & y_t = E_t y_{t+1} - \varphi (i_t - E_t \pi_{t+1}) + g_t \quad (10b) \\ & i_t \geq -r^* \quad (10c) \\ & u_t = \rho_u u_{t-1} + \varepsilon_{u,t} \quad (10d) \\ & g_t = \rho_g g_{t-1} + \varepsilon_{g,t} \quad (10e) \\ & u_0, g_0 \text{ given} \end{aligned}$$

fails to be recursive, since constraints (10a) and (10b) involve forward-looking variables. For this reason dynamic programming techniques cannot be applied directly, as these assume transition equations that do not involve expectation terms. To obtain a dynamic programming formulation of the

there is no significant autocorrelation left in the innovations $\varepsilon_{i,t}$ ($i = u, g$). Also when estimating AR(2) processes the additional lags remain insignificant.

¹³This contrasts with Ireland (2002) who uses data starting from 1948:1. Extending our sample back to this date would also lead to highly persistent u -shocks. Since we do not argue that monetary policy has been constant across the extended sample, we decide to stick to the shorter period.

¹⁴When using instead the period 1979:4-1995:2 as in Rotemberg and Woodford (1998), which includes the volatile years 1980-1982, we find an annual standard deviation of 2.7 percent for the estimated real rate process.

problem at hand we apply the techniques of Marcet and Marimon (1998). Doing so delivers the following recursive optimization problem:

$$W(\mu_t^1, \mu_t^2, u_t, g_t) = \inf_{\gamma_t^1, \gamma_t^2} \sup_{y_t, \pi_t, i_t} \quad (h(y_t, \pi_t, i_t, \gamma_t^1, \gamma_t^2, \mu_t^1, \mu_t^2, u_t, g_t) \\ + \beta E_t [W(\mu_{t+1}^1, \mu_{t+1}^2, u_{t+1}, g_{t+1})]) \quad (11)$$

$$\begin{aligned} \text{s.t.: } & i_t \geq -r^* \\ & \mu_{t+1}^1 = \gamma_t^1 \\ & \mu_{t+1}^2 = \gamma_t^2 \\ & u_{t+1} = \rho_u u_t + \varepsilon_{u,t+1} \\ & g_{t+1} = \rho_g g_t + \varepsilon_{g,t+1} \\ & \mu_0^1 = 0 \\ & \mu_0^2 = 0 \\ & u_0, g_0 \text{ given} \end{aligned}$$

where

$$h(y, \pi, i, \gamma^1, \gamma^2, \mu^1, \mu^2, u, g) \equiv -\alpha y^2 - \pi^2 + \gamma^1 (\pi - \lambda y - u) - \mu^1 \pi \\ + \gamma^2 (y + \varphi i - g) - \mu^2 \frac{1}{\beta} (\varphi \pi + y). \quad (12)$$

Problem (11) is fully recursive as all transition equations now involve only lagged state variables.

A crucial feature of the reformulated problem (11) is that it introduces two co-state variables (μ^1, μ^2) bringing the total number of state variables up to four. The states (μ^1, μ^2) are the lagged values of the Lagrange multipliers for the constraints (10a) and (10b), respectively; they can be interpreted in terms of ‘promises’ that have to be kept from past commitments. A negative value for μ^1 , for example, indicates a promise to generate higher inflation rates than what purely forward looking policy would imply.¹⁵ Likewise, a negative value of μ^2 indicates a promise to generate higher values for $\frac{1}{\beta}(\varphi \pi + y)$ than suggested by purely forward looking policy.

We then use numerical dynamic programming tools to approximate the value function that solves the recursive saddle point functional equation (11)

¹⁵This follows from the expression for the one-period return function $h(\cdot)$ given in equation (12).

and derive the associated policy functions.¹⁶ Solutions have been computed in MatLab employing the toolboxes provided by Miranda and Fackler (2002). The results of this numerical exercise are reported in the next sections.

6.2 Optimal Interest Rate Policy

This section describes the optimal commitment policy in the presence of the zero lower bound on interest rates for the model calibration illustrated in the previous section.

Before presenting the results we would like to emphasize that the presence of the zero lower bound generates nonlinear optimal policies and therefore causes a failure of certainty-equivalence. This has two important implications.

First, the average values of endogenous variables will generally differ from their deterministic steady state in a way that depends on the nature of shocks.

Second, the average or expected model dynamics in response to shocks will differ from the deterministic impulse responses. For this latter reason we will discuss results in terms of the implied ‘mean dynamics’ in response to shocks instead of the more familiar deterministic impulse responses.¹⁷

6.2.1 Optimal policy reaction functions

Figure 4 presents the marginal responses of (y, π, i) and the Lagrange multipliers (γ^1, γ^2) in the optimal commitment solution to a mark-up shock and a real rate shock, respectively.¹⁸ The responses of the Lagrange multipliers are of interest because they represent commitments regarding future inflation rates and output levels, as explained in the previous section. Note that figure 4 depicts the optimal policy responses both for the case when the zero lower bound is imposed (solid line) and for the case when interest rates are allowed to become negative (dashed line with circles). Policies are shown for a range of ± 4 unconditional standard deviations of the mark-up shock and real rate shock, respectively.

¹⁶In particular, we used projection methods based on polynomial splines to approximate the value function solving equation (11) and derive the associated policy functions.

¹⁷Mean dynamics are identical to impulse responses whenever certainty equivalence holds, e.g., in the absence of the zero lower bound. We found that in our nonlinear model the mean dynamics can differ considerably from the deterministic impulse responses.

¹⁸The state variables not shown on the x -axes are set to their (unconditional) average values.

The left-hand panel of figure 4 shows that the optimal policy response to mark-up shocks is almost unaffected by the presence of the zero lower bound.¹⁹ Independently of whether the bound is present or not, a positive mark-up shock, i.e., a negative supply shock, increases inflation, lowers output, and leads to a promise of future deflation, as indicated by the positive value of γ^1 . The latter ameliorates the inflationary effects of the current mark-up shocks through the expectational channel present in equation (1). To deliver on the promise, the policymaker increases nominal interest rates to generate a slight deflation in the future.²⁰

The nominal interest rate response to the mark-up shock reveals why the presence of the zero bound does not significantly affect optimal policy. When considering a 4 standard deviation value of the mark-up shock the required nominal rate adjustments are in the order of only 10 basis points (in annual terms); the bound, therefore, virtually never binds.

The situation is quite different when considering the policy response to a real rate shock, which is shown on the right-hand panel of figure 4. While real-rate shocks do not generate any policy trade-off when interest rates are allowed to become negative, once the zero lower bound is imposed large negative demand shocks cause it to bind. As a result, the policymaker employs promises of future inflation as a substitute for nominal rate cuts to lower real rates.²¹ This causes, via the expectational channel present in equation (1), current inflation to be above zero. Due to the welfare costs associated with positive inflation rates, the negative output effects of negative real rate shocks are not completely undone and output falls below potential.

6.2.2 Dynamic response to real rate shocks

Figure 5 displays the mean dynamics of the economy in response to real rate shocks of ± 3 unconditional standard deviations.²² With our calibration

¹⁹The optimal reaction to mark-up shocks is different with or without the bound but the difference is quantitatively small for the chosen parameter values. We will come back to this point in section 6.2.3 discussing the implications of binding negative real rate shocks.

²⁰The sign of the optimal interest rate response, however, depends on the degree of autocorrelation of the mark-up shocks. In particular, with less persistent shocks nominal rates would optimally decrease in response to positive mark-up shocks.

²¹The fact that the policy maker promises future inflation follows from $\gamma^1 + \frac{\varphi}{\beta}\gamma^2 < 0$, see the discussion in section 6.1.

²²The initial values for the other states have been set equal to their unconditional average values. The mean dynamics in this and other graphs are the average responses for 100 thousand stochastic simulations.

the annual equilibrium real rate then stands temporarily at +8.48% and -1.48%, respectively, with the interesting case being the one where full use of productive resources requires a negative real rate.

As argued by Krugman (1998), negative real rates may well be plausible, even if the marginal product of physical capital is positive. For instance agents may require a large equity premium, as historically observed in the U.S., or the price of physical capital may be expected to decrease.

Figure 5 shows that a positive real rate shock has no noticeable effect on output and inflation. The increase in the natural rate of interest can be implemented via an increase in nominal interest rates. This causes output to perfectly mimic the natural rate of output and leaves inflation at its target value of zero. The same would be true for a negative real rate shock if interest rates were allowed to become negative.

In the presence of the zero lower bound, however, real rates have to be cut by letting inflation increase above zero. Figure 5 shows that inflation increases by about 0.6% annually for a considerable amount of time and only slowly returns to a value close to zero. Output which is initially negative rises to about 0.5% above its potential for several quarters, while interest rates remain at their lower bound for about three quarters and only slowly return to the value consistent with the zero inflation steady state.

Getting out of a ‘liquidity trap’ generated by negative real-rate shocks, thus, requires that the policymaker commits to letting future output and inflation increase above zero for a substantial amount of time. The qualitative feature of this finding has already been reported in Eggertsson and Woodford (2003) and in somewhat different form in Auerbach and Obstfeld (2003). Clearly, ex-post there would be strong incentives to increase nominal interest rates earlier than promised as this would bring both inflation and output closer to their target values. The feasibility of the optimal policy response, therefore, crucially depends on the policymaker’s credibility. Whether policymakers can and want to credibly commit to such policies is currently subject of debate, see for example Orphanides (2003).

An important question is then the following: What does the need of employing output-induced inflation rates to achieve real rates cuts imply for the ability of the central bank to achieve its target values of output and inflation? Our simulations show that there are virtually no level effects for output and inflation for the calibration at hand. Although output and inflation are somewhat larger than zero on average, the effects are in the order of less than 0.02% for both variables.

The effects on output and inflation are small because the zero lower bound on nominal interest rates binds infrequently, namely one quarter every 28 years on average. Moreover, once the zero bound becomes binding, it remains so for about 1.8 quarters on average. Figure 7 displays the probability with which the zero bound is binding for n quarters under optimal policy, conditional on it being binding in quarter one. The (conditional) likelihood that nominal interest rates are zero for more than 4 quarters is thus a mere 3.9%.

6.2.3 Dynamic response to mark-up shocks

Surprisingly, the presence of binding negative real rate shocks alters the optimal policy response to other shocks, i.e., the reaction to positive real rate shocks and mark-up shocks of both signs.²³

To understand how this effect emerges, consider the optimal reaction to real rate shocks, as shown in figure 5. As is clearly shown in the lowest panel, the real rate rises by more in response to positive real rate shocks than by how much it falls in response to negative real rate shocks. Thus, with real rate shocks alone this would imply a positive real rate bias. This cannot be an equilibrium phenomenon, since (in a stationary equilibrium) the policymaker is unable to affect the average real rate, as argued in section 3.

To compensate for this positive real rate bias the policymaker reacts with lower real rates to positive and negative mark-up shocks. This is illustrated in figure 6 which plots the economy's mean response to positive and negative mark-up shocks. The left-hand panel illustrates the response when the zero lower bound is imposed and the right-hand panel depicts the case where nominal rates can become negative. The bottom panels in figure 6 clearly indicate that real rate is lowered more (increased less) when the bound is imposed. Admittedly, the effects are quantitatively small for the present parameterization but are more pronounced if the real rate process is more variable.²⁴

It is worth mentioning that a similar effect can be observed when considering the reaction to positive real rate shocks. Real rates are generally

²³The effects for the positive real rate shocks are small, as discussed at the end of this section, and therefore do not show up for the scaling of the y -axes used in figure 5.

²⁴More variable real rates cause the lower bound to bind more often and thereby reinforce the importance of the asymmetric reaction to positive and negative real rate shocks.

increased by less in response to positive real rate shocks when the lower bound is imposed. This generates small positive output gaps in response to positive real rate shocks. Yet, for the calibration at hand this effect is again quantitatively small.

6.2.4 Summary

A number of positive results regarding the zero lower bound emerge from this analysis. First, mark-up shocks are far too small to cause the zero bound to bind. Second, while real-rate shocks may cause the lower bound to bind, this happens relatively rarely and, in addition, is an element of optimal policy. Moreover, by creating the right inflationary expectations (and by credibly committing to fulfill them later on) the economy can get rather quickly out of the binding region. Finally, targeting an average inflation rate of zero seems not to create any problem for the U.S. economy.

Obviously, one may wonder about the robustness of these conclusions. For example, central bankers may reasonably be concerned about the fact that future shocks are larger or more persistent than was the case in the past. These and similar questions are addressed in the next section.

6.3 Sensitivity Analysis and Discussion

We now analyze the robustness of the previous results by considering a number of variations to our baseline calibration. Particular attention is given to the sensitivity of the results to changes in the parameterization of the shock processes.

6.3.1 More Variable Shocks

We estimated the shock processes using data for a time period that most economists would consider to be relatively ‘calm’ especially when confronted with the more ‘turbulent’ 1960s and 1970s. Since one cannot exclude that more ‘turbulent’ times might lie ahead, it seems to be of interest to study the implications of optimal policy with more variable mark-up and real rate shocks. In this regard, this section considers the sensitivity of our findings to increasing the shock variances σ_u^2 and σ_g^2 above the values for our baseline parameterization.

Increasing the variance of mark-up shocks we find that the results are remarkably stable. This holds even when increasing the variance of σ_u^2 tenfold above its estimated value. Average output and average (annual) inflation

are slightly positive but still below 0.02% each. Also the average number of quarters that zero nominal rates occur remains within 0.1 quarters of the value reported for the baseline case. Zero nominal rates then occur slightly more frequently, roughly once every 22,5 years (versus 28 years for the baseline), mainly because negative mark-up shocks now interact with negative real-rate shocks and cause the lower bound to become binding somewhat more often.

The picture changes somewhat increasing the variance of real rate shocks. Figure 8 displays the response of average output, inflation, and the average frequency and duration of zero nominal interest rates to changes in the (annual unconditional) standard deviation of the real rate shock process. Reactions of these variables are shown for up to a tenfold increase in the variance of real rate shocks compared to the baseline calibration.

The top two panels in figure 8 illustrate that average output and average inflation are both increasing in the standard deviation of the real rate process. Yet, the reaction of both variables is quite moderate. Average inflation (and therefore nominal rates) remains below 1% annually and average output is less than 0.1% above its natural rate on average.

The positive level effects differ considerably from those reported in earlier contributions. Uhlig (2000), for example, reports negative level effects when analyzing optimal policy for a backward-looking model. Clearly, the gains from promising positive values for future output and inflation cannot show up in a backward-looking model. Orphanides and Wieland (1998) report negative level effects for a forward-looking model but consider Taylor-type interest rate rules rather than optimal rules as in this paper.

The third and forth panel in figure 8 show that the average frequency with which zero nominal rates occur under optimal policy is quite sensitive to the variance of the real rate process. Increasing the variance by a factor of 3 already causes zero nominal rates to occur once every five years on average, a considerable drop compared to the 28 years found for the baseline case. At the same time, however, the average duration of zero nominal rates increases only slightly and is still in the order of about 2 quarters.

Therefore, except for the frequency with which zero nominal rates occur under optimal policy, the results for the baseline calibration seem quite robust to an increase in the variance of mark-up shocks and real rate shocks.

6.3.2 Lower Interest Rate Elasticity of Output

Our benchmark calibration assumes an interest rate elasticity of output of $\varphi = 6.25$. Although one may claim that this value is on the high side of plausible estimates for the intertemporal elasticity of substitution, it may be capturing non-modeled interest-rate-sensitive investment decisions, see Chapter 4 in Woodford (2003). Nevertheless, we also considered the case $\varphi = 1$, which would correspond to log utility in consumption for a model without capital. In particular, we re-estimated the shock processes with this assumption and then computed the optimal policies for a range of ± 4 standard deviations of the shocks.²⁵

We find that level effects for output and inflation are negligible and that mark-up shocks remain unable to cause zero nominal interest rates. Once zero nominal rates do occur, they last for about 2 quarters on average, which is in line with the value for the baseline calibration. However, zero nominal interest rates now occur much more often, namely about once every 10 years on average. In line with the evidence reported in figure 8, we find that this change is entirely due to the higher variability of the real rate process implied by $\varphi = 1$.²⁶ Changing the interest rate sensitivity of output, therefore, does not lead to substantially different results.

7 Conclusions

In this paper we assess the quantitative importance of the zero lower bound on nominal interest rates for optimal monetary policy in the U.S.. The analysis suggests that the existence of a zero lower bound does not deliver a strong rationale for implementing positive average inflation rates. Even an average inflation rate of 1% is hard to justify as an optimal outcome within the present model.

A qualitatively new feature that emerges in this paper is that the presence of a zero lower bound might alter the optimal reaction to non-binding shocks. The existence of a zero lower bound, therefore, might well affect optimal policy, even when the bound is far from being binding.

Obviously, credibility of the central bank is key for our results. In fact the use of expected inflation is unavailable to a discretionary policymaker

²⁵ Except for the parameters of the shock processes and for $\varphi = 1$, all other parameters were as in section 5.

²⁶ In particular, the identified real shock process now has an annual standard deviation of 2.00% which is more than 20% higher than in our baseline calibration.

who would have the incentive to renege on any such commitment ex-post. Therefore, assessing the welfare costs associated with discretionary policy making in the presence of a zero lower bound seems to be of considerable interest. This question is taken up in a companion paper by Adam and Billi (2003) where we determine the optimal nonlinear discretionary monetary policy when imposing the zero lower bound.

8 Appendix

8.1 REE with Zero Bound

We prove the claims of proposition 1 reported in the main text. Let

$$z_t = \begin{pmatrix} \pi_t \\ y_t \end{pmatrix}, \quad v_t = \begin{pmatrix} u_t \\ g_t \end{pmatrix}, \quad m = \begin{pmatrix} 0 \\ \varphi r^* \end{pmatrix} \text{ and } \varepsilon_t = \begin{pmatrix} \varepsilon_t^u \\ \varepsilon_t^g \end{pmatrix}.$$

For $i_t \equiv -r^*$ the model is then given by

$$M_0 z_t = m + M_1 E_t z_{t+1} + v_t, \quad (13)$$

where

$$M_0 = \begin{pmatrix} 1 & -\lambda \\ 0 & 1 \end{pmatrix} \text{ and } M_1 = \begin{pmatrix} \beta & 0 \\ \varphi & 1 \end{pmatrix}$$

and

$$v_t = R v_{t-1} + \varepsilon_t \quad \text{with } R = \begin{pmatrix} \rho_u & 0 \\ 0 & \rho_g \end{pmatrix}.$$

Defining $\tilde{z}_t \equiv z_t - \bar{z}$ where the steady state value \bar{z} is given by

$$\bar{z} = \begin{pmatrix} -r^* \\ -\frac{1-\beta}{\lambda} r^* \end{pmatrix}$$

one can rewrite (13) as

$$M_0 \tilde{z}_t = M_1 E_t \tilde{z}_{t+1} + v_t \quad (14)$$

In a REE we have

$$E_t \tilde{z}_{t+1} = \tilde{z}_{t+1} + \eta_{t+1} \quad (15)$$

where the forecast error η_{t+1} is a martingale difference series. Substituting (15) into (14) delivers the equilibrium law of motion

$$\tilde{z}_{t+1} = A\tilde{z}_t - Bv_t - \eta_{t+1},$$

where $A = M_1^{-1}M_0$ and $B = M_1^{-1}$. As is easily verified, A has one unstable eigenvalue $e_1 > \frac{1}{\beta}$ and one stable eigenvalue $e_2 \in (0, 1)$.

Now express the forecast error η_{t+1} as a combination of the fundamental innovations and sunspot innovations, i.e.

$$\eta_{t+1} = -C\varepsilon_{t+1} - D\gamma_{t+1},$$

where the sunspots γ_{t+1} are a 2 by 1 martingale difference sequence, while C and D denote arbitrary matrices. We then have

$$\tilde{z}_{t+1} = A\tilde{z}_t - Bv_t + C\varepsilon_{t+1} + D\gamma_{t+1}. \quad (16)$$

Since the matrix B has full rank, the shocks v_t will put \tilde{z}_t on the unstable subspace of A , even if C and D would restrict ε_{t+1} and γ_{t+1} to lie on the stable subspace. Since the eigenvector associated with the explosive eigenvalue is of the form

$$\vec{e}_1 = \begin{pmatrix} 1 \\ -e \end{pmatrix}$$

for some $e > 0$, \tilde{y}_t and $\tilde{\pi}_t$ will diverge into opposite directions. This proves the existence of a continuum of locally explosive (sunspot) REE.

We now consider stationary solutions. For the reasons discussed above, the only way the solutions (16) can be stationary is if there is a common factor in the lag polynomials that allows to eliminate the term $A\tilde{z}_t$. Rewrite (16) as

$$\begin{aligned} (I - AL)\tilde{z}_{t+1} &= -Bv_t + C\varepsilon_{t+1} + D\gamma_{t+1} \\ &= -Bv_t + C(v_{t+1} - Rv_t) + D\gamma_{t+1} \\ &= (I - (B + CR)C^{-1}L)Cv_{t+1} + D\gamma_{t+1} \end{aligned} \quad (17)$$

which shows that there is a common factor if $A = (B + CR)C^{-1}$, which requires

$$vecC = [(I \otimes A) - (R' \otimes I)]^{-1} vecB$$

The previous equation implies that $C = \Gamma$ where Γ is given by equation (9). From (17) it then follows that

$$\begin{aligned}\tilde{z}_{t+1} &= \Gamma v_{t+1} + (I - AL)^{-1} D \gamma_{t+1} \\ &= \Gamma v_{t+1} + \sum_{n=0}^{\infty} (AL)^n D \gamma_{t+1}\end{aligned}\tag{18}$$

If D projects the sunspots γ on the unstable manifold of A then these solutions are again explosive with y_t and π_t diverging into opposite directions. Now suppose the eigenspace of D is restricted to the stable manifold of A . The solutions (18) are then stationary. The subspace generated by the eigenvector associated with the stable eigenvalue of A is

$$\vec{e}_2 = \begin{pmatrix} \frac{-e_2\beta+\varphi\lambda+\beta}{\varphi} \\ 1 \end{pmatrix},$$

where both entries of \vec{e}_2 are positive. The matrix D then has a representation of the form $D = \vec{e}_2 \cdot (d_1, d_2)$ for some constants d_1 and d_2 . Choosing $s_t = (d_1, d_2) \cdot \gamma_t$, $\phi = e_2$, $w = \frac{-e_2\beta+\varphi\lambda+\beta}{\varphi}$, and applying the definition of \tilde{z}_t causes (8) and (18) to be equivalent.

References

- Adam, Klaus and Roberto M. Billi**, “Optimal Discretionary Monetary Policy with a Zero Bound on Nominal Interest Rates,” *University of Frankfurt Mimeo*, 2003.
- Auerbach, Alan J. and Marurice Obstfeld**, “The Case for Open-Market Purchases in a Liquidity Trap,” *NBER Working Paper No. 9814*, 2003.
- Benhabib, Jess, Stephanie Schmitt-Grohé, and Martín Uribe**, “Avoiding Liquidity Traps,” *Journal of Political Economy*, 2002, 110, 535–563.
- Calvo, Guillermo A.**, “Staggered Contracts in a Utility-Maximizing Framework,” *Journal of Monetary Economics*, 1983, 12, 383–398.
- Clarida, Richard, Jordi Galí, and Mark Gertler**, “The Science of Monetary Policy: Evidence and Some Theory,” *Journal of Economic Literature*, 1999, 37, 1661–1707.

- , —, and —, “Monetary Policy Rules and Macroeconomic Stability: Evidence and Some Theory,” *Quarterly Journal of Economics*, 2000, 115, 147–180.
- , —, and —, “Optimal Monetary Policy in Open versus Closed Economies: An Integrated Approach,” *American Economic Review Papers and Proceedings*, 2001, 91, 248–252.
- Coenen, Günter and Volker Wieland**, “The Zero-Interest-Rate Bound and the Role of the Exchange Rate for Monetary Policy in Japan,” *Journal of Monetary Economics*, 2003, 50, 1071–1101.
- Eggertsson, Gauti**, “How to Fight Deflation in a Liquidity Trap: Committing to Being Irresponsible,” *IMF Working Paper 03/64*, 2003.
- and Michael Woodford, “The Zero Bound on Interest Rates and Optimal Monetary Policy,” *Princeton University Mimeo*, 2003.
- Evans, George and Seppo Honkapohja**, “Policy Interaction, Expectations and the Liquidity Trap,” *mimeo*, 2003.
- Fuhrer, Jeffrey F. and Brian F. Madigan**, “Monetary Policy When Interest Rates Are Bounded at Zero,” *Review of Economic Studies*, 1997, 79, 573–585.
- Ireland, Peter**, “Technology Shocks in the New Keynesian Model,” 2002. Boston College *mimeo*.
- Krugman, Paul R.**, “It’s Baaack: Japan’s Slump and the Return of the Liquidity Trap,” *Brookings Papers on Economic Activity*, 1998, 49(2), 137–205.
- Marcet, Albert and Ramon Marimon**, “Recursive Contracts,” *Universitat Pompeu Fabra Working Paper*, 1998.
- McCallum, Bennett T.**, “Japanese Monetary Policy, 1991-2001,” *Federal Reserve Bank of Richmond Economic Quarterly*, 2003, 89/1.
- Miranda, Mario J. and Paul L. Fackler**, *Applied Computational Economics and Finance*, Cambridge, Massachusetts: MIT Press, 2002.
- Orphanides, Athanasios**, “Monetary Policy in Deflation: The Liquidity Trap in History and Practice,” *Federal Reserve Board Mimeo*, 2003.

- and Volker Wieland, “Price Stability and Monetary Policy Effectiveness When Nominal Interest Rates are Bounded at Zero,” *Federal Reserve Board, FEDS Working Paper No. 35*, 1998.
- and —, “Efficient Monetary Policy Design Near Price Stability,” *Journal of the Japanese and International Economies*, 2000, 14, 327–365.
- Reifschneider, David and John C. Williams**, “Three Lessons for Monetary Policy in a Low-Inflation Era,” *Journal of Money Credit and Banking*, 2000, 32, 936–966.
- Rotemberg, Julio J. and Michael Woodford**, “An Optimization-Based Econometric Model for the Evaluation of Monetary Policy,” *NBER Macroeconomics Annual*, 1998, 12, 297–346.
- Schmitt-Grohé, Stephanie and Martin Uribe**, “Optimal Fiscal and Monetary Policy under Sticky Prices,” *University of Pennsylvania mimeo*, 2001.
- Svensson, Lars E. O.**, “Escaping from a Liquidity Trap and Deflation: The Foolproof Way and Others,” *Journal of Economic Perspectives (forthcoming)*, 2003.
- Uhlig, Harald**, “Should We Be Afraid of Friedman’s Rule?,” *Journal of Japanese and International Economies*, 2000, 14, 261–303.
- Wolman, Alexander L.**, “Real Implications of the Zero Bound on Nominal Interest Rates,” *forthcoming Journal of Money Credit and Banking*, 2003.
- Woodford, Michael**, “Doing Without Money: Controlling Inflation in a Post-Monetary World,” *Review of Economic Dynamics*, 1998, 1, 173–209.
- , “Optimal Monetary Policy Inertia,” *NBER Working Paper Series No. 7261*, 1999.
- , “Inflation Stabilization and Welfare,” *NBER Working Paper No. 8071*, 2001.
- , *Interest and Prices*, Princeton: Princeton University Press, 2003.

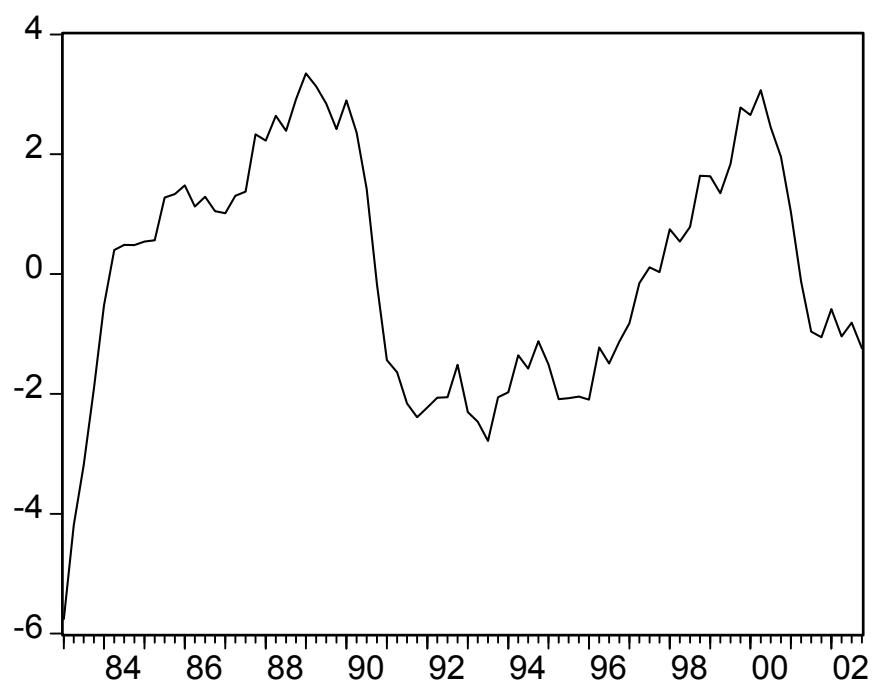


Figure 1: Detrended U.S. output

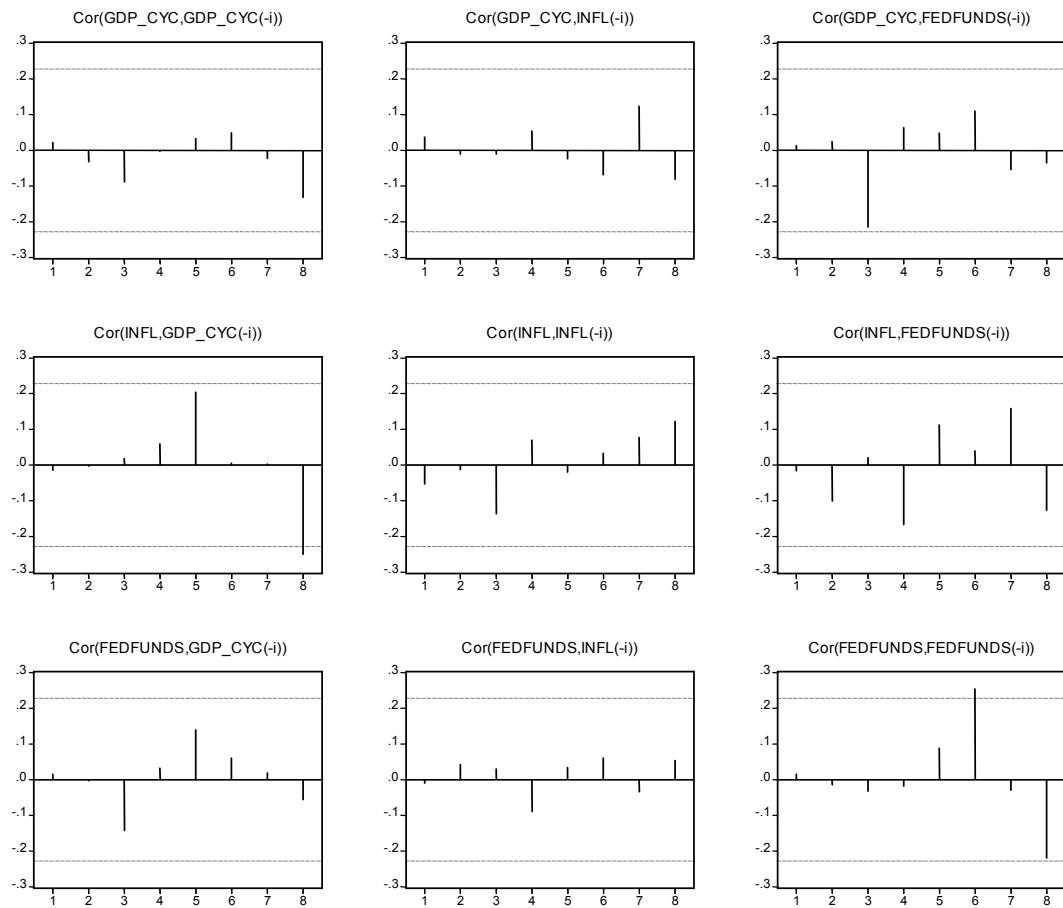


Figure 2: Residual autocorrelations with 2 s.d. error bounds for an unrestricted VAR in GDP, inflation, and fed funds rate.

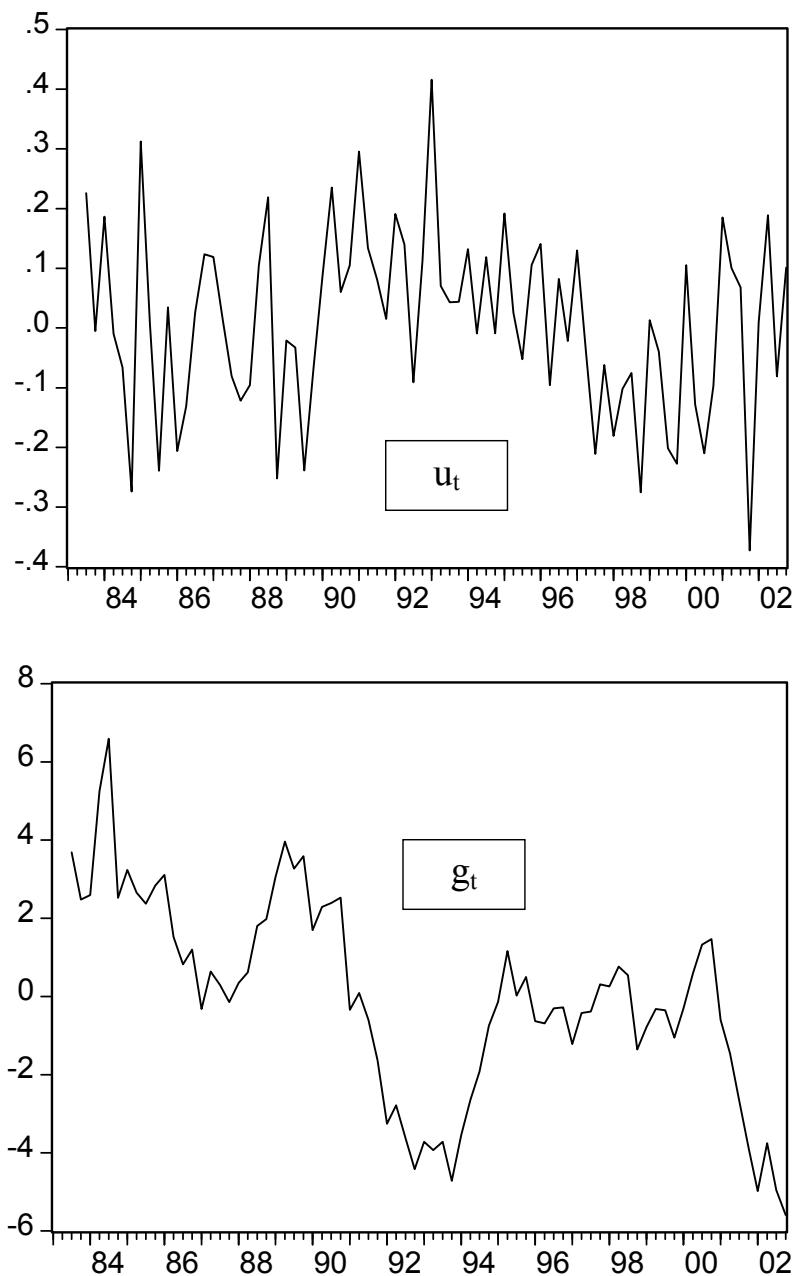


Figure 3: Identified shock processes

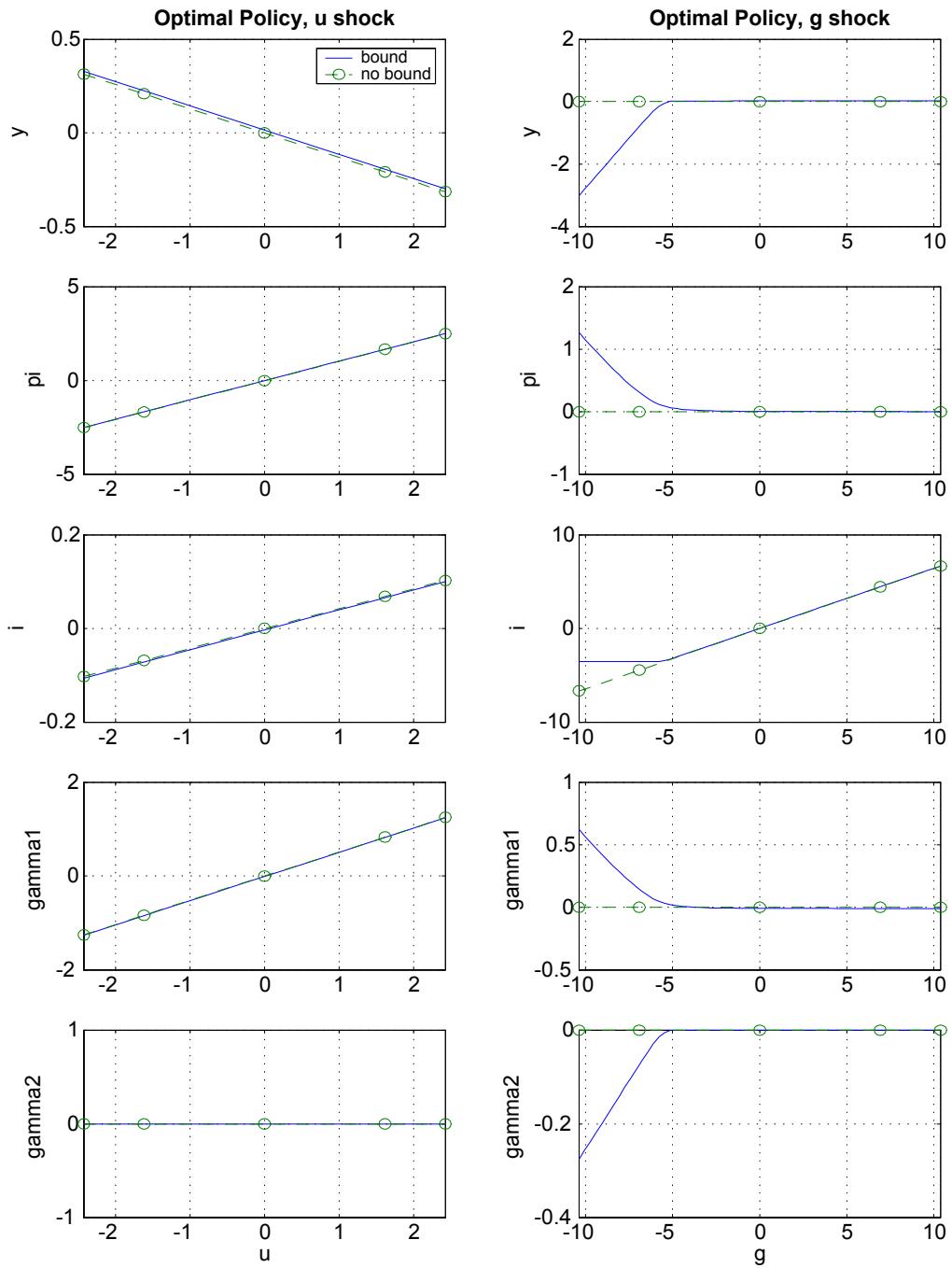


Figure 4: Optimal policy responses (baseline calibration)

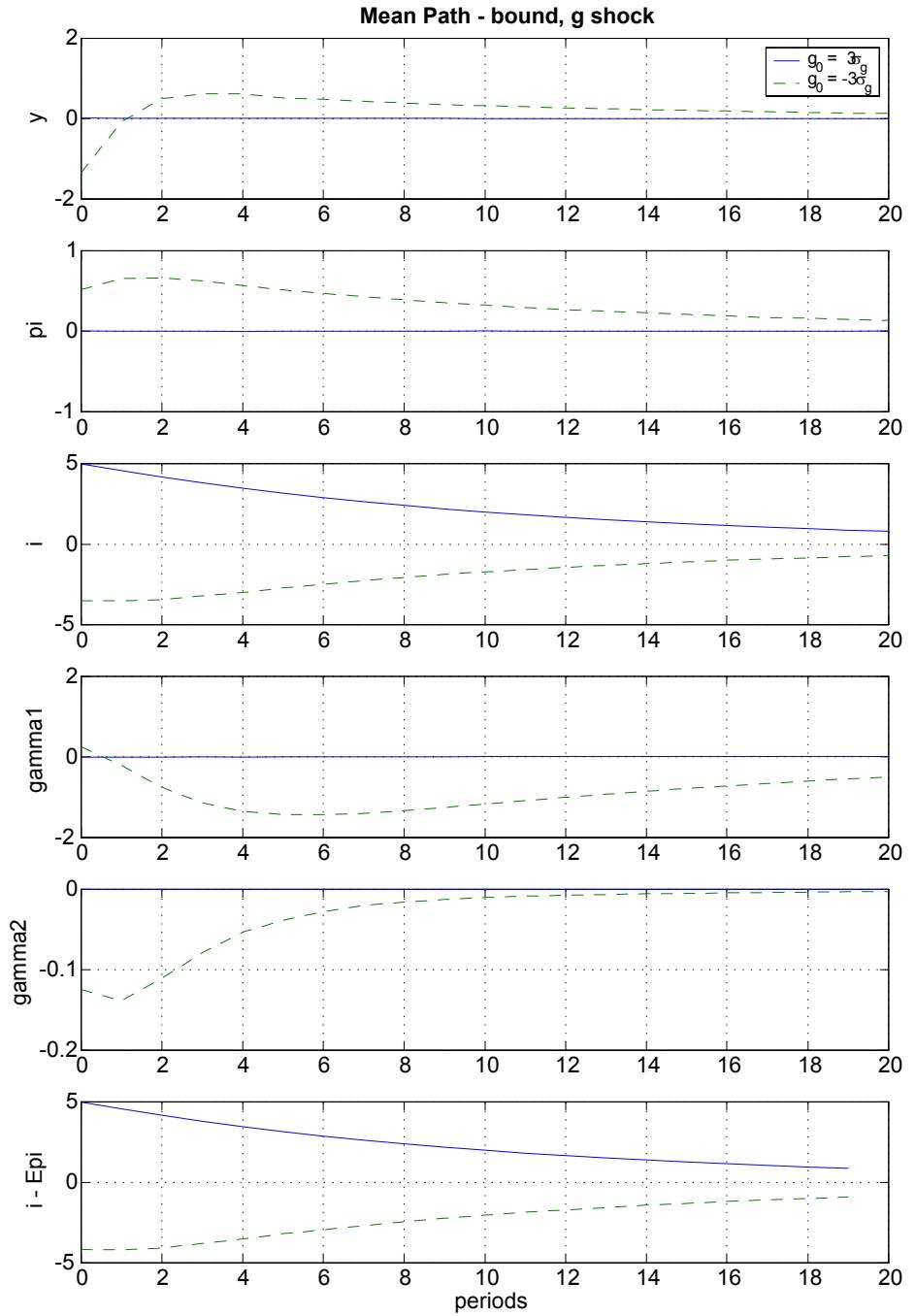


Figure 5: Mean response to ± 3 s.d. real rate shocks (baseline calibration)

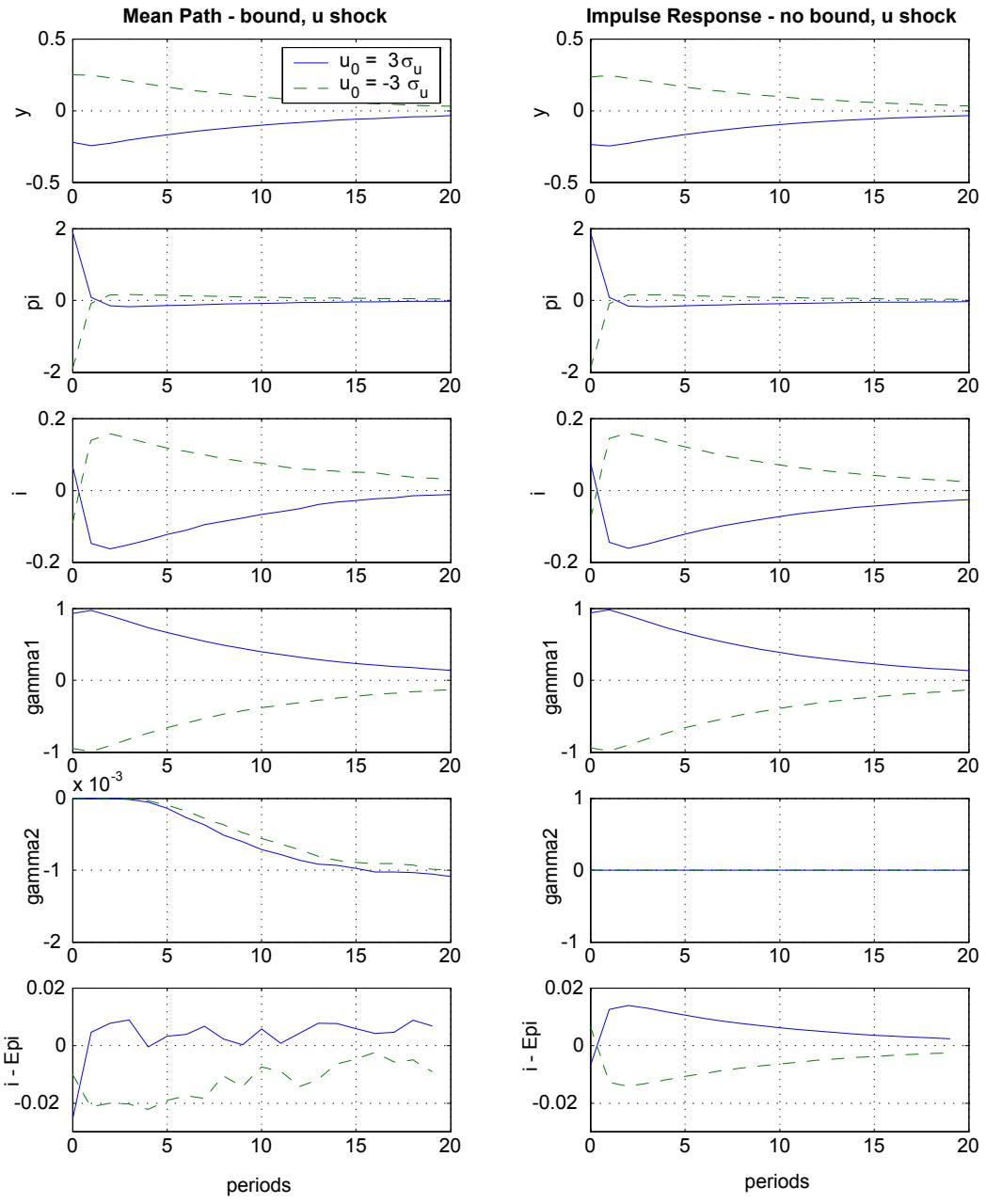


Figure 6: Mean response to ± 3 s.d. mark-up shock (baseline calibration)

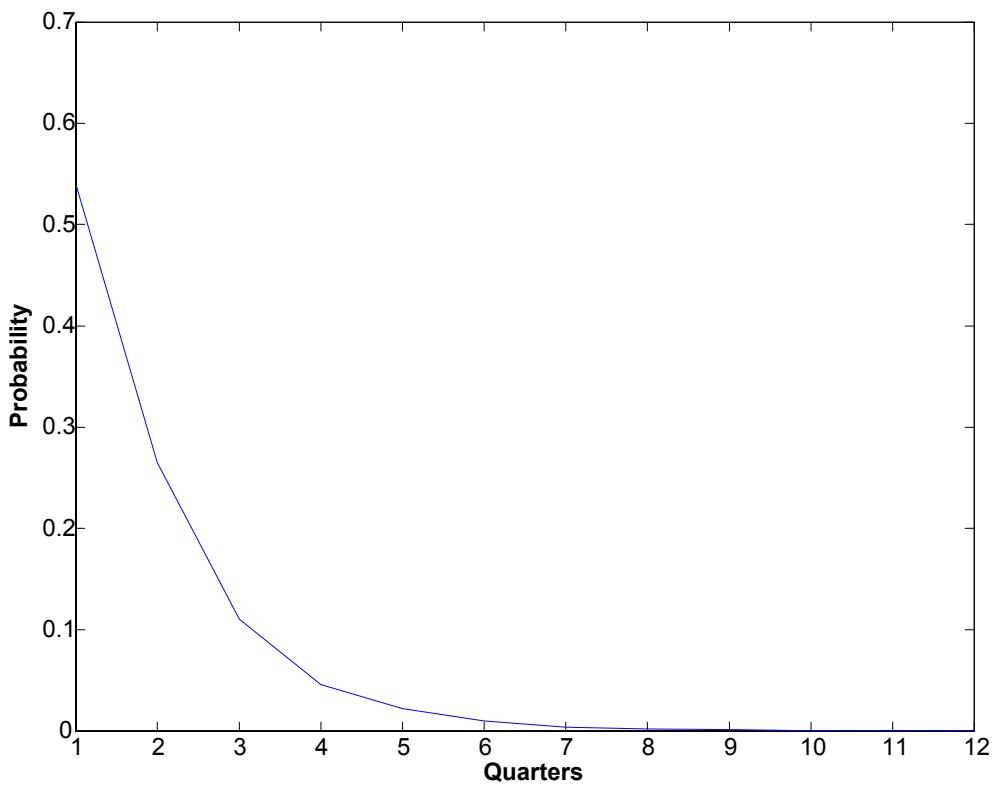


Figure 7: Persistence of zero interest rates (baseline calibration)

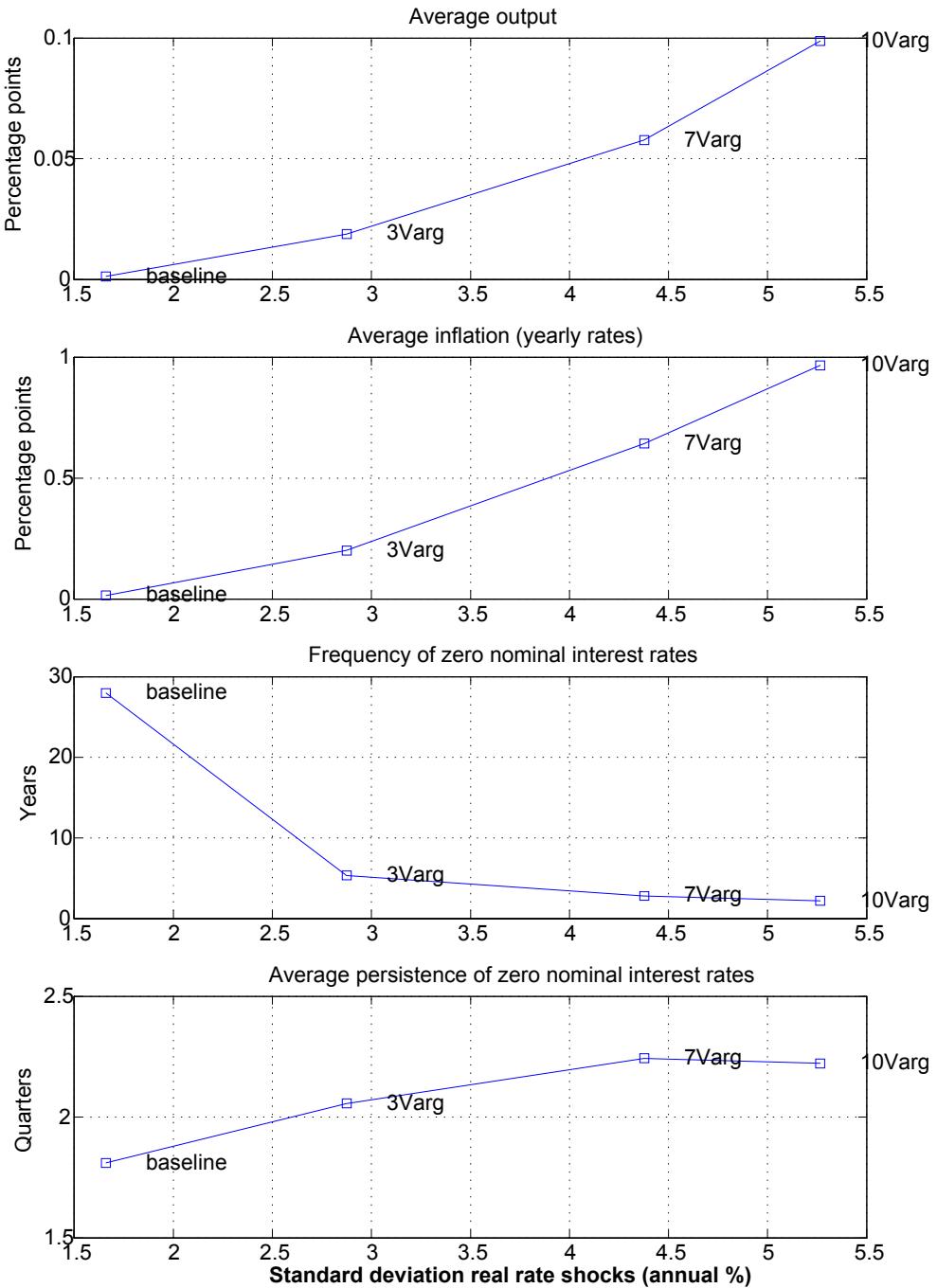


Figure 8: Sensitivity analysis for the variance of real rate shocks