The State-Dependent Effects of Monetary Policy

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Abstract

This paper studies state-dependent effects of monetary policy shocks. I first consider state-dependence of policy actions in a simple static model. The model predicts that effectiveness of monetary policy is positively related to the level of output. I next use an estimated DSGE model to quantitatively assess asymmetries in policy transmission mechanism. Consistent with the intuition from the simple model, I find that the effects of monetary policy on output are less powerful in recessions compared to expansions. By contrast, inflation is more sensitive in recessionary states. The latter implies that the aggregate price flexibility is varying across the business cycle. In particular, prices are more flexible when the economy is in a recessionary state. Conversely, prices become more rigid in expansionary states.

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1. Introduction

The power of monetary policy to spur a flagging economy has been long debated. The issue has recently regained its popularity in the light of the recent economic crisis. The current paper once again addresses the question by studying state-dependence in monetary policy transmission mechanism in an estimated medium-scale DSGE model. This work is a small part of a broader overarching research topic: propagation of macroeconomic shocks over the business cycle.

I start the analysis with a simple static model. It features myopic firms that are subject to price rigidities as in the Calvo model. Under some simplifying assumptions on preferences and monetary policy, I show that policy shifts have large effects on output in periods in which output is relatively high. Moreover, higher price stickiness amplifies state-dependent effects of policy actions.

To quantitatively assess asymmetries in policy transmission mechanism, I next introduce a medium-scale DSGE model similar to Schmitt-Grohe and Uribe (2005), Christiano et al. (2005) and Smets and Wouters (2007). The model is estimated on U.S. data using Bayesian methods. To account for state-dependence in policy effects, I first solve the model via a second order approximation. The model is then used to simulate expansionary and recessionary state vectors for computing generalized impulse response functions. The results imply that the effects of policy actions on real economy are limited in recessions. On the contrary, monetary measures are more efficient in expansionary states. Within this, consumer expenditure is the most sensitive components of output, whereas the response of investment does not vary significantly across the states of the economy. Meanwhile, the response of inflation to monetary policy interventions is smaller in expansions compared to recessions. The latter implies that aggregate price flexibility varies across the business cycle.

In particular, aggregate price flexibility is higher in recessions, while it is relatively lower in expansions.

In a recent study, Vavra (2014) concludes that policy is indeed less efficient during recessions. He argues that prices are more flexible in times of high uncertainty, and as uncertainty is countercyclical, nominal shocks (as well as monetary shocks) do not propagate to the real economy in any significant way. Bachmann et al. (2019) confirm the findings in Vavra (2014) by looking at the effects of time-varying business volatility on price setting behavior in the German economy. In both papers, asymmetries in policy transmission mechanism mainly stem from state-dependent price stickiness at the extensive margin.[1] As Klenow and Kryvtsov (2008) show, in U.S. data, movements in the aggregate inflation are mostly due to changes at the intensive margin. Likewise, in the baseline model of this paper, the frequency of price adjustment is fixed, so it is only the intensive margin that matters.

When simulating the model, I depart from the existing literature by using multiple indicator variables (state vectors) for identification of the prevailing business cycle state. It is a long tradition mostly in the empirical literature to define states with a single indicator variable (threshold variable). Usually, it is output growth or some measure of capacity utilization (e.g. output gap). This approach, however, disregards co-movement of state variables over the cycle and may potentially distort the results of the analysis.

State-dependence in transmission mechanism has important implications for monetary policy implementation. In periods of poor growth, the Central Bank has to deal with worsening trade-off between inflation and output growth: it is not

[1] According to Caballero and Engel (2007), the price response to current shocks can be decomposed into intensive and extensive margins. The intensive margin shows the further price increase of the firms that are able to adjust at the current period. The extensive margin represents the change in the population of adjusters.

able to generate the necessary additional impulse to boost the economy without creating huge inflationary pressures. Therefore, monetary authorities may need to apply to unconventional policy measures to achieve the desired expansionary effect.

This paper is related to different strands of literature. A small group of empirical papers studies how the effects of monetary policy vary over the business cycle. Earlier contributions include, among others, Cover (1992), Thoma (1994), Weise (1999), Smets and Peersman (2001) and Garcia and Schaller (2002). Recent papers include, among others, Lo and Piger (2005), Angrist et al. (2018) and Tenreyro and Thwaites (2016). These studies mostly rely on non-linear VARs and related time series models. The current paper, by contrast, is based on a study of a fully-specified DSGE model.

The theoretical literature has not had much to say about state-dependent effects of monetary policy across the business cycle. Vavra (2014) and Baley and Blanco (2019) are the most prominent works that look at this issue. The focus of these papers, however, is on the role of uncertainty in propagation of monetary shocks. The current research follows the methodology in Sims and Wolff (2018). The latter, however, focuses on variability in the effects of tax shocks across the business cycle, whereas this paper deals with state-dependent effects of monetary policy shocks.

The remaining of the paper is structured as follows. The second section employs a simple static model to study state-dependence in the effects of monetary policy shocks. The third section introduces a medium-scale DSGE model featuring various frictions. The model is estimated on U.S. data via Bayesian methods. The fourth section gives the main quantitative results concerning state-dependent effects of policy shocks. It next discusses the sources of state-dependence in the structural model. Finally, it shows that the central results of the paper are not sensitive to the choice of price setting mechanism. The last section summarizes and concludes the analysis.

2. State-Dependence in Simple Model

This section explores the effects of monetary policy shifts in a simple static model. The model is populated by a representative household, a continuum of firms, and a monetary authority. The household receives a utility flow from consumption and disutility from labor. The firms operate under monopolistic competition and produce differentiated goods by using a linear technology in labor. They set prices as in Calvo (1983). The monetary authority controls inflation by using a simple Taylor-type interest rate rule. I will neglect the dynamic aspects of the model and concentrate on a static version of the framework. The overall purpose of this section is to provide intuition for how exogenous policy changes might affect output differently over the business cycle. The simple model is not meant to provide any definitive answers, but rather serves as motivation for the following quantitative analysis.

Period utility from consumption and labor takes the following form:

$$U(C_t, N_t) = \ln C_t - N_t \tag{1}$$

C_t is consumption and N_t is labor. The optimality conditions are as follows:

$$\frac{1}{C_t} = \beta(i_t + 1)E_t \frac{1}{C_{t+1}(\pi_{t+1} + 1)} \tag{2}$$

$$C_t = w_t \tag{3}$$

π_t is inflation rate, i_t is the nominal interest rate and w_t is the real wage. To make the model static, assume that $E_t C_{t+1} = \bar{C}$ and $E_t \pi_{t+1} = \bar{\pi}$, where $\bar{C}$ and $\bar{\pi}$ are long-run values of consumption and inflation, respectively.

Monetary policy is conducted using a simple Taylor-type interest rate rule:

$$(i_t + 1) = (\pi_t + 1)^{\phi_\pi} m_t \tag{4}$$

where $\phi_\pi > 1$ captures the response parameter to inflation. m_t is an exogenous monetary policy shock.

Given the market-clearing condition ($Y_t = C_t$), the household optimality condition (2), and the policy rule (4), one can get:[2]

$$\frac{1}{Y_t} = \beta(\pi_t + 1)^{\phi} m_t \tag{5}$$

Next, consider the price setting behaviour of firms. As in the Calvo model, a share of θ firms keep their former price and $1 - \theta$ firms update their price. Inflation dynamics can, thus, be written as:

$$\pi_t + 1 = \left(\frac{1 - (1 - \theta)(p_t^{op})^{1-\epsilon}}{\theta}\right)^{\frac{1}{\epsilon - 1}} \tag{6}$$

where p_t^{op} is the optimal re-setting price, ϵ is the price elasticity of demand of goods. Firms are myopic, i.e. the optimal prices are not set in a forward-looking manner. Given the firms' market power, the price is set as a constant markup over the marginal cost:

$$p_t^{op} = \frac{\epsilon}{\epsilon - 1} mc_t = \frac{\epsilon}{\epsilon - 1} Y_t^{\sigma} \tag{7}$$

[2]I leave out $\bar{Y}$ and $\bar{\pi}$ without loss of generality.

(5), (6) and (7), together implicitly determine Y_t as a function of monetary policy shock, m_t:

$$\pi_1(Y_t, m_t) = \pi_2(Y_t) \tag{8}$$

Totally differentiate (8) to evaluate the impact of the policy shock on output:

$$\epsilon_{m_t,Y_t} = -\frac{\frac{\partial \pi_1}{\partial m_t}}{\frac{\partial \pi_1}{\partial Y_t} - \frac{\partial \pi_2}{\partial Y_t}} \tag{9}$$

(9) can be used to show that, for a given m_t, the impact of a policy change positively depends on the level of output, $\frac{\partial \epsilon_{m_t,Y_t}}{\partial Y_t} > 0$. Intuitively, strict concavity of the pricing relation (6) implies that price sensitivity to policy shocks declines with the strength of the economy. To put it differently, in states where output is high, a shift in monetary policy leads to greater changes in output and smaller changes in inflation. The first panel of Figure 1 plots on the vertical axis how the effect of monetary shocks on output varies for different values of output. The second panel shows the impact of monetary shocks on inflation for different values of output. The figures confirm the latter assertion that the effectiveness of policy in affecting output is procyclical.

Consistent with the intuition developed above, one would also expect that increasing price flexibility dampens the state-dependent effects of policy shocks. The third panel in Figure 1 displays the effects of policy shifts on output for different values of price stickiness parameter, θ. The figure shows that state-dependence in policy actions becomes stronger as prices get more rigid.

To conclude, the simple static model implies that efficiency of monetary policy is procyclical. More generally, while the presented model is useful for developing overall intuition, to have a quantitative assessment of asymmetries in policy transmission, one needs a more detailed theoretical framework with a number of frictions parameterized to match empirical observations. I turn to this exercise in the next section.

3. A Medium-Scale General Equilibrium Model

The current section describes the model environment that is employed to get a quantitative assessment of asymmetries in monetary policy transmission mechanism. I consider a conventional medium-scale DSGE model along the lines of Schmitt-Grohe and Uribe (2005), Christiano et al. (2005) and Smets and Wouters (2007). The model economy is populated by a representative household, a competitive final good firm, a continuum of intermediate goods firms, and a Central Bank. To produce plausible quantitative conclusions concerning the effects of monetary policy over the business cycle, the model is estimated via Bayesian methods.

3.1. Households

An infinitely-lived representative household seeks to maximize the present discounted value of flow utility function over consumption and labor:

$$E_0 \sum_{i=1}^{\infty} \beta^t \mu_t \frac{((C_t - hC_{t-1})^{\phi}(1-N_t)^{1-\phi})^{1-\sigma} - 1}{1-\sigma} \tag{10}$$

C_t is the aggregate consumption index, N_t is the labor supply and μ_t is a preference shock. Preferences allow for internal habit formation measured by the parameter h.

The household owns the capital stock. The latter accumulates according to:

$$K_{t+1} = (1 - \Omega(\frac{I_t}{I-t-1}))I_t Z_t + (1-\delta)K_t \tag{11}$$

Investment at t is denoted by I_t and δ is the depreciation rate. Following Christiano et. al. (2005), $\Omega() = \frac{\tau}{2}(\frac{I_t}{I_{t-1}} - 1)^2$ measures investment adjustment costs. Z_t is a shock to the marginal efficiency of investment. Justiniano et al (2010) indicate the importance of this shock in business cycle fluctuations.

As in Schmitt-Grohe and Uribe (2007), I assume that the household supplies labor to a continuum of labor markets of measure one. Labor demand in each market i is given by:

$$N_{i,t} = (\frac{w_{i,t}}{w_t})^{-\epsilon_w} N_t^d \tag{12}$$

$w_{i,t}$ and w_t denote the real wage in market i and the real wage in the whole economy, respectively. N_t^d is the aggregate labor demand and $\epsilon_w > 1$ measures labor substitutability in different markets. In the model, nominal wages are sticky a la Calvo (1983). Each period, the household can set the nominal wage optimally in a fraction $1 - \theta$ $(0 \leq \theta_w < 1)$ of arbitrary chosen labor markets. Non-updated nominal wages are indexed to the previous period's inflation rate with an indexation parameter ξ_w. N_t is the total labor supplied by the household. It satisfies $N_t = \int_0^1 N_{i,t} di$.

The household faces the following period by period budget constraint:

$$C_t + I_t + \Lambda(u_t)K_t + \frac{B_t}{P_t} = \int_0^1 w_{i,t}N_{i,t}di + r_t u_t K_t + (1 - i_{t-1})\frac{B_{t-1}}{P_t} + \Pi_t \tag{13}$$

The aggregate price index is denoted by P_t. B_{t-1} is the stock of nominal bonds with which the household enters period t. The nominal interest rate on bonds is given by i_t. Π_t denotes profit resulting from the household's ownership of firms. The capital utilization rate is given by u_t. Working capital stock more intensively is costly. The cost is measured in units of physical capital and is given by the function $\Lambda(u_t) = \phi_0(u_t - 1) + \frac{1}{2}\phi_1(u_t - 1)^2$.

The optimality conditions of the household's problem are listed below:

$$\lambda_t = \beta E_t \lambda_{t+1} \frac{i_t + 1}{\pi_{t+1} + 1} \tag{14}$$

$$w_t^{op} = \frac{\epsilon_w}{\epsilon_w - 1} \frac{X_{1,t}^w}{X_{2,t}^w} \upsilon_{w,t} \tag{15}$$

$$X_{1,t}^w = \mu_t U_N(.) w_t^{\epsilon_w} N_t^d + \theta_w \beta E_t (\pi_t + 1)^{-\epsilon_w \xi_w} (\pi_{t+1} + 1)^{\epsilon_w} X_{1,t+1}^w \tag{16}$$

$$X_{2,t}^w = \mu_t w_t^{\epsilon_w} N_t^d + \theta_w \beta E_t (\pi_t + 1)^{-\epsilon_w \xi_w} (\pi_{t+1} + 1)^{\epsilon_w} X_{2,t+1}^w \tag{17}$$

$$r_t = \Lambda'(u_t) \tag{18}$$

$$q_t Z_t (1 - \Omega(\frac{I_t}{I_{t-1}}) - \Omega'(\frac{I_t}{I_{t-1}}) \frac{I_t}{I_{t-1}}) + \beta E_t \frac{\lambda_{t+1}}{\lambda_t} q_{t+1} Z_{t+1} \Omega'(\frac{I_{t+1}}{I_t})(\frac{I_{t+1}}{I_t})^2 = 1 \tag{19}$$

$$q_t = \beta E_t \frac{\lambda_{t+1}}{\lambda_t} (r_t u_t - \Lambda(u_{t+1}) + (1 - \delta) q_t) \tag{20}$$

$$\lambda_t = \mu_t U_C(t) - \beta h \mu_{t+1} U_C(t+1) \tag{21}$$

In these conditions, λ_t is the marginal utility of consumption. q_t is the relative price of capital in terms of consumption good. w_t^{op} is the optimal real reset wage and $\upsilon_{w,t}$ is a wage markup shock.

3.2. Final Good Firm

The aggregate output in the economy is produced by a representative, competitive firm. It bundles intermediate goods into a single product by the following technology:

$$Y_t = \left(\int_0^1 Y_{j,t}^{\frac{\epsilon_p - 1}{\epsilon_p}} dj \right)^{\frac{\epsilon_p}{\epsilon_p - 1}} \tag{22}$$

ϵ_p is the elasticity of substitution between different varieties. The representative firm takes the aggregate price level, P_t, and the price of intermediate goods, $P_t(j)$, as given. It chooses intermediate good quantities, $Y_t(j)$ to maximize profits. The usual demand schedule is given by:

$$Y_{j,t} = (\frac{P_{j,t}}{P_t})^{-\epsilon_p} Y_t \tag{23}$$

The zero profit condition of the representative firm yields the following relation for the aggregate price level:

$$P_t = \left(\int_0^1 P_{j,t}^{1-\epsilon_p} \, dj \right)^{\frac{1}{1-\epsilon_p}} \tag{24}$$

3.3. Intermediate Goods Firms

A continuum of competitive monopolists produce differentiated goods using labor and capital services (the product of physical capital and utilization) according to the following production function:

$$Y_{j,t} = A_t \bar{K}_{j,t}^{\alpha} N_{j,t}^{1-\alpha} \tag{25}$$

A_t is a common productivity factor. The standard cost minimization problem implies:

$$mc_t = \frac{w_t^{1-\alpha} r_t^{\alpha}}{A_t} \frac{(1-\alpha)^{\alpha-1}}{\alpha^{\alpha}} \tag{26}$$

$$\frac{\bar{K}_{j,t}}{N_{j,t}} = \frac{\alpha}{1-\alpha} \frac{w_t}{r_t} \tag{27}$$

mc_t denotes real marginal cost. Factor prices and productivity are common for all intermediate firms. Thus, the intermediate goods firms choose capital services and labor in the same ratio.

The prices are sticky as in Calvo (1983). In every period, each firm faces a constant probability, $1-\theta_p$, of being able to adjust its nominal price. The ability to adjust prices is independent across the firms and time. Similar to Christiano et al. (2005), those firms which are unable to optimize their prices in the current period automatically index them to the previous period's inflation. ξ_p is the indexation parameter.

All firms face common marginal cost. Accordingly, all updating firms select the same reset price. The latter can be written as:

$$\pi_t^{op}+1=\frac{\epsilon_p}{\epsilon_p-1}(\pi_t+1)\frac{X_{1,t}^p}{X_{2,t}^p}\upsilon_{p,t} \tag{28}$$

$$X_{1,t}^p=\lambda_t Y_t mc_t+\beta\theta_p E_t(\pi_t+1)^{-\epsilon_p\xi_p}(\pi_{t+1}+1)^{\epsilon_p}X_{1,t+1}^p \tag{29}$$

$$X_{2,t}^p=\lambda_t Y_t+\beta\theta_p E_t(\pi_t+1)^{(1-\epsilon_p)\xi_p}(\pi_{t+1}+1)^{\epsilon_p-1}X_{2,t+1}^p \tag{30}$$

$\pi_t^{op}+1=\frac{P_t^{op}}{P_{t-1}}$, where P_t^{op} is the optimally reset price. $\upsilon_{p,t}$ is a price markup shock as in Smets and Wouters (2007).

3.4. Monetary Policy

The Central Bank follows a simple interest rate rule:

$$i_t=(1-\rho_i)i+\rho_i i_{t-1}+(1-\rho_i)(\phi_\pi(\pi_t-\pi)+\phi_Y(\ln Y_t-\ln Y_{t-1}))+m_t \tag{31}$$

ρ_i describes interest-rate smoothing. ϕ_π and ϕ_Y control the responses to inflation and output growth. The letters without a time subscript mark corresponding steady-state values. Finally, m_t is a monetary policy shock.

3.5. *Aggregation and Equilibrium*

Summing up demand functions for intermediate goods, using the fact that all intermediate good firms hire capital services and labor in the same proportion, and imposing market-clearing for labor implies the following aggregate production function for economy:

$$Y_t = \frac{A_t \bar{K}_t^{\alpha} N_t^{\alpha}}{d_t^p} \tag{32}$$

$d_t^p = \int_0^1 (\frac{P_{j,t}}{P_t})^{-\epsilon_p} dj$ describes relative price dispersion. It can be written as:

$$d_t^p = ((1-\theta_p)(\pi_t^{op}+1)^{-\epsilon_p} + \theta_p(\pi_{t-1}+1)^{-\epsilon_p \xi_p} d_{t-1}^p)(\pi_t+1)^{\epsilon_p} \tag{33}$$

Labor market clearing implies:

$$N_t = N_t^d d_t^w \tag{34}$$

$d_t^w = \int_0^1 (\frac{w_{i,t}}{w_t})^{-\epsilon_w} di$ measures wage dispersion. The later evolves as:

$$d_t^w = (1-\theta_w)(\frac{w_t^{op}}{w_t})^{-\epsilon_w} + \theta_w(\frac{w_{t-1}}{w_t})^{-\epsilon_w} \frac{(\pi_{t-1}+1)^{-\epsilon_w \xi_w}}{(\pi_t+1)^{\epsilon_w}} d_{t-1}^w \tag{35}$$

Aggregate inflation is given by:

$$(\pi_t+1)^{1-\epsilon_p} = (1-\theta_p)(\pi_t^{op}+1)^{1-\epsilon_p} + \theta_p(\pi_{t-1}+1)^{(1-\epsilon_p)\xi_p} \tag{36}$$

In a similar way, the aggregate real wage evolves as:

$$w_t^{1-\epsilon_w} = (1-\theta_w)(w_t^{op})^{1-\epsilon_w} + \theta_w(\pi_{t-1}+1)^{(1-\epsilon_w)\xi_w}(\pi_t+1)^{\epsilon_w-1} w_{t-1}^{1-\epsilon_w} \tag{37}$$

Finally, the aggregate resource constraint for the economy has the following form:

$$Y_t = C_t + I_t + \Lambda(u_t)K_t \tag{38}$$

The model features six exogenous processes: the neutral productivity, A_t, the marginal efficiency of investment, Z_t, the preference shock, μ_t, the price and wage markup shocks, $v_{p,t}$ and $v_{w,t}$, and the monetary policy shock, m_t. The first five of them follow mean zero $AR(1)$ processes in the log with shocks drawn from standard normal distributions

$$\ln A_t = \rho_A \ln A_{t-1} + e_{A,t} \tag{39}$$

$$\ln Z_t = \rho_Z \ln Z_{t-1} + e_{Z,t} \tag{40}$$

$$\ln \mu_t = \rho_\mu \ln \mu_{t-1} + e_{\mu,t} \tag{41}$$

$$\ln v_{p,t} = \rho_{v_p} \ln v_{p,t-1} + e_{v_p,t} \tag{42}$$

$$\ln v_{w,t} = \rho_{v_w} \ln v_{w,t-1} + e_{v_w,t} \tag{43}$$

Finally, monetary policy shock, m_t is drawn from a normal distribution with zero mean and standard deviation σ_m.

3.6. Parameter Values

Some of the parameter values are set to match long run targets or to conventional values in the literature. The rest are estimated via Bayesian methods. The list of calibrated parameters is shown in Table 1.

The rest of the parameters are estimated via Bayesian approach. The estimation is based on U.S. data. The data covers the period 1984Q1-2008Q4.[3] The observables are the growth rates of consumption, investment, labor, real wage, the level of inflation and the nominal interest rate. Consumption is the sum of personal consumption expenditures on nondurable goods and services. Investment is the sum of personal consumption expenditures on durable goods and gross private fixed investment. Hours worked is defined as the product of average weekly hours in the non-farm business sector with total civilian employment aged sixteen and over. Real wage is the hourly compensation in the nonfarm business sector. The nominal interest rate is the three-month Treasury Bill rate. Inflation is the change in the price index for personal consumption expenditures. The real series are obtained by deflating the corresponding nominal series by the GDP deflator. The data is obtained from the FRED database.

Table 2 presents the estimation results. The estimated parameters are generally in-line with the existing estimates in the literature. The results on nominal rigidity parameters imply that price and wage contracts last about 4.2 and 4.7 quarters, respectively. Also, there are small amounts of price and wage indexation, $\xi_w = 0.49$ and $\xi_p = 0.45$. The estimated habit persistence parameter is $h = 0.72$. This value is quite standard. The estimated values for the utility function parameters are $\gamma = 0.29$ and $\sigma = 2.48$. These are similar to the values in Christiano et al. (2011) and Sims and Wolff (2018). My estimate of the investment adjustment cost parameter is $\tau = 4.26$. The latter is in the range of values found in the literature. The estimated values for labor and product substitutability parameters are 21.1 and 20.42, respectively. The resulting steady-state markups are 4.9% in labor market and 5.1% in the product market. These estimates are consistent with that of Altig et

[3] The end date is chosen so as to exclude the zero lower bound period as the paper does not deal with the latter issue.

al. (2011) and Kuester (2010). The estimated values for the Taylor rule parameters are as follows. The smoothing component is $\rho_i = 0.79$, the response to inflation is $\phi_\pi = 1.51$, and the response to output growth is $\phi_Y = 0.14$. The rest of the parameters (including standard deviations of shocks) are listed in Table 2.

Overall, the estimated model fits the data quite well. The model-implied relative volatility of consumption and investment are about 0.5 and 2.5, respectively. These are close to the corresponding values in the data. Similarly, the model replicates cross-correlations between the growth rates of output, consumption, and investment.[4]

The estimated model implies that productivity and marginal efficiency of investment shocks explain more than 50 percent of the unconditional variance of output growth. Price markup shocks account for about 25 percent of output's variance. Preference shocks, wage markup shocks and monetary policy shocks explain the remaining 25 percent of the output's volatility.

4. Quantitative Results

This section explores the effects of monetary policy over the state space. I start the section by describing the procedure of computing non-linear impulse response functions. I next study the effects of monetary policy across recessionary and expansionary states. I also explore the sources of state-dependence in policy transmission mechanism.

[4]The model-implied cross-correlations are $corr(dc, dy) = 0.55$ and $corr(dI, dy) = 0.81$. The corresponding values in the data are 0.64 and 0.82, respectively.

4.1. State-Dependent Impulse Response Functions

The model is solved at the mean of the posterior distribution of the parameters by second-order approximation. To evaluate state-dependent effects of policy shocks, one needs to solve the model via an approximation of order higher than one. The impulse response function of a variable x_t to a shock to monetary policy m_t is defined as the difference between forecasts of x_t at time t and $t-1$, conditional on the realization of the shock at t:

$$IRF_j = (E_t x_{t+j} - E_{t-1} x_{t+j} \mid s_{t-1}, m_t) \tag{44}$$

where j is the response horizon. The responses are computed via simulations following the procedure of Koop et al. (1996). Given the vector of initial states, I simulate the model by drawing random sequences of shocks. These are baseline simulations. Next, I use the same sequences of shocks, except I replace the first shock with the monetary policy shock of interest (alternative simulations). This procedure is repeated $N = 100$ times. The response is the difference between the mean paths of alternative and baseline simulations.

Impulse response functions at higher orders of approximation depend upon the prevailing state values, s_{t-1} (starting conditions) in which a shock hits the economy.[5] In this setting, state-dependence can be explored by choosing suitable values of state vectors. The next section outlines the procedure of choosing the state vectors for quantitative simulations.

[5] They also depend on the magnitude and sign of the shock. However, these elements are not considered in the current paper.

4.2. Baseline results

For baseline analysis, I simulate 1000 periods of data from the model starting from the non-stochastic steady-state. These are the state vectors that will serve as starting conditions for computing impulse responses. When simulating the states, I set the standard deviation of the monetary policy shock to zero. The aim is to ensure that any state-dependence in monetary transmission mechanism is not related to the current state of policy.[6] Recessionary states are defined from episodes in the simulated sample path with output below the mean value for at least two consecutive periods. Otherwise, the economy is in expansion. From the above defined two groups of state vectors, I compute impulse responses to a contractionary monetary policy shock.

Figures 2 displays impulse response functions of output to a contractionary 25 basis point monetary shock for the simulated 1000 states. We observe that there is notable degree of state-dependence in the effects of monetary policy shocks. First, consider the impact response of output to the shock. The average value across the states is 0.27 while the lowest and the highest values are 0.18 and 0.36, respectively. Next, the maximum response of output to the shock, is, on average, 0.40. The lowest value is about three times smaller than the highest value. The latter are 0.21 and 0.59, respectively. Note that the average impact response is smaller than the average maximum response, i.e. the peak effect of policy shifts on output occurs after several periods. In particular, the figure shows that policy shocks generally have their largest effect after approximately 4 quarters. The last result is in line with that of Smets and Wauters (2007).

I next turn to studying possible state-dependent effects of policy shocks across

[6] The results are not sensitive to doing this.

the two groups of states. Figure 3 plots time series of maximum response (in absolute values) across the 1000 simulated states (blue line) and the simulated values of output (black line). We can observe that the two series strongly co-move.[7] Consistent with the intuition in the static model of Section 3, the maximum response values tend to be low in periods where output is below the average. This pattern is made clear by the impulse responses presented in Figure 4. The figure shows average responses of the selected variables to a contractionary policy shock. The magnitude of the shock is the same as before, 25 basis points. We can observe that the effects of policy on economic activity are, on average, more pronounced in expansionary states compared to recessionary states. We also observe that output (and its components) is more responsive to policy shifts in expansions than at the ergodic mean. Table 3 presents summary on the effects of a policy shock on the economy at recessionary and expansionary states. It reports the average values of impact and maximum responses for selected variables. Focusing on the maximum responses, the average output response in expansions is about 16% larger than in recessions. For consumption and investment the differences are 28% and 3%, respectively. As a matter of fact, consumption expenditure is the most sensitive components of output. Meanwhile, the responses of investment are somewhat similar in both states of the economy. We also observe that, unlike output, the average inflation response in recessions is more pronounced than in expansions. These results imply that aggregate price flexibility varies across the business cycle. In particular, price flexibility is higher in recessionary states, while it is relatively lower in expansionary states. This is somewhat similar to the findings in Vavra (2014) and Bachmann et. al. (2018), with an exception that in the latter, higher volatility is the main cause of increased

[7]The correlation coefficient between the series is 0.72.

price flexibility.

The asymmetric effects of policy shifts become more pronounced in deep recessions and booms. I define booms as the states where simulated output is in its highest 80th percentile.Deep recessions are the states where simulated output is in its lowest 20th percentile. The corresponding average impulse response functions are presented on Figure 5. Table 4 reports the average values of impact and maximum responses for selected variables across booms and deep recessions. The magnitude of the shock is the same as before, 25 basis points. Consider the maximum responses. The response of output in booms is about 39% larger than in deep recessions. For investment and consumption, the differences are 50% and 3%, respectively. Once again, the state-dependence in output responses are mainly due to consumption, whereas the behaviour of investment is somewhat similar across the states. Lastly, the average response of inflation in deep recessions is about 8% larger than in booms.

4.3. Dissecting the Sources of State-Dependence in the Baseline Model

The preceding analysis has shown that there are notable asymmetries in the effects of monetary policy. A deeper insight into the sources of state-dependence can be gained by considering alternative parametrizations such that a particular friction in the model is affected. The results of this experiment are shown in Table 5. It reports average maximum responses across the recessionary and expansionary states for selected variables under baseline and alternative parametrizations.

I start with parameters that influence the behavior of the household. First, I decrease habit formation in preferences by setting $h = 0.1$ (columns labeled $h = 0.1$). Doing so raises average maximum response values both in recessionary and in expansionary states. However, it also dampens the state-dependent effects of policy shocks on output and its components cross the two set of states.

On the investment side of the model, consider making the capital utilization more costly, i.e. set $\phi_1 = 10$ (columns labeled $\phi_1 = 10$ in the table). This results in a decrease in response values and makes state-dependent effects less significant. Next, consider columns labeled $\tau = 10$. They report the average maximum response values when capital adjustment cost is set to $\tau = 10$. Similar to increasing capital utilization costs, this tends to notably decrease average maximum response values in both states. It also results in a reduction in state-dependent effects of policy actions across the expansions and recessions.

On the production side, I consider state-dependent effects of policy shocks under different degrees of price and wage stickiness. First, I make wages more flexible, in particular I set $\theta_w = 0.1$ (columns labeled $\theta_w = 0.1$). This results in a notable decrease in average maximum response values in both states. On the other hand, the asymmetric effects of policy actions are moderately amplified across the two set of states. Finally, consider making prices more flexible, i.e. set $\theta_p = 0.1$ (columns labeled $\theta_p = 0.1$). Doing this not only decreases the average responses across the states but also dampens asymmetric effects of policy shocks. The last result is very much inline with that of the static model of Section 3.

5. State-Dependence under Rotemberg Pricing

In Section 3, I present a simple stylized model to explain the intuition behind the state-dependence in policy actions. The key element in the model is the Calvo price setting behaviour of firms and the resulting particular form of inflation equation. Section 4 shows that the baseline DSGE model preserves the main conclusions of the simple model. To ensure that the baseline results are not entirely driven by

Calvo mechanism, I consider an alternative price setting scheme. In particular, I assess state-dependence in policy under the Rotemberg model of price adjustment.

In Rotemberg (1982), each intermediate firm faces quadratic costs of adjusting prices in terms of final goods. I also assume partial indexation to the previous period's inflation similar to Ireland (2007). The adjustment cost is given by:

$$\frac{\eta}{2}\left(\frac{P_{j,t}}{(1+\pi_{t-1})^{\xi_p}P_{j,t-1}}-1\right)^2 Y_t \tag{45}$$

Inflation dynamics can be written as:

$$1-\phi\left(\frac{\pi_t+1}{(\pi_{t-1}+1)^{\xi_p}}-1\right)\frac{\pi_t+1}{(\pi_{t-1}+1)^{\xi_p}}+\eta\beta\frac{\lambda_{t+1}}{\lambda_t}\eta\left(\frac{\pi_{t+1}+1}{(\pi_t+1)^{\xi_p}}-1\right)\frac{\pi_{t+1}+1}{(\pi_t+1)^{\xi_p}}\frac{Y_{t+1}}{Y_t}=(1-u_{p,t}mc_t)\epsilon_p \tag{46}$$

The aggregate resource constraint is given by:

$$Y_t = C_t + I_t + \Lambda(u_t)K_t + \frac{\eta}{2}\left(\frac{\pi_t+1}{(\pi_{t-1}+1)^{\xi_p}}-1\right)^2 Y_t \tag{47}$$

The rest of the equilibrium conditions as the same as before. The parametrization of the model is the same as in benchmark model with Calvo pricing. As for the adjustment cost parameter, I set $\eta = \frac{\theta(\epsilon-1)}{(1-\theta)(1-\theta\beta)}$. This ensures that the two versions of the model are equivalent to first order.

Table 6 displays the average values of impact and maximum responses for selected variables across expansions and recessions in the model with Rotemberg pricing. We observe that the impact of monetary shocks on the real economy is stronger in expansions than in recessions. Moreover, almost all of the effect is attributable to the response of consumption. In sum, both versions of the model deliver qualitatively similar results on the effectiveness of monetary policy over the business cycle.

6. Conclusions

Policy transmission mechanism is one of the most heavily investigated topics in monetary economics. This paper takes another perspective on the problem by studying state-dependencies in the transmission mechanism in a fully specified general equilibrium framework. I show that the impact of monetary policy on the real economy is more pronounced in expansionary states compared to recessions. Meanwhile, prices are less responsive in expansions than in recessions. This basically implies that aggregate price flexibility varies across the business cycle. Moreover, the state-dependent effects of policy shocks become stronger in deep recessions and expansions. I also study the main sources of state-dependence in policy transmission mechanism. Consistent with the intuition from the stylized model, price rigidity is an integral factor of asymmetric policy effects in the structural model. Finally, the simulations from the model with Rotemberg pricing show that the main results of the papers are not dependent on Calvo mechanism.

References

[1] Altig, David, Lawrence J. Christiano, Martin Eichenbaum and Jesper Lindé, "Firm-specific Capital, Nominal Rigidities and the Business Cycle", Review of Economic Dynamics 14 (2011), 225-247.

[2] Angrist, Joshua D., Oscar Jorda, and Guido Kuersteiner, "Semiparametric Estimates of Monetary Policy Effects: String Theory Revisited", Journal of Business Economic Statistics, Taylor Francis Journals 36 (2018), 371-387.

[3] Bachmann, Ruediger, Benjamin Born, Steffen Elstner and Christian Grimme, "Time-varying Business Volatility, Price Setting, and the Real Effects of Monetary Policy", Journal of Monetary Economics 101 (2019), 82-99.

[4] Baley, Isaac and Julio A. Blanco, "Firm Uncertainty Cycles and the Propagation of Nominal Shocks", American Economic Journal: Macroeconomics 11 (2019), 276-337.

[5] Caballero Ricardo J. and Eduardo M.R.A. Engel, "Price Stickiness in Ss Models: New Interpretations of Old Results", Journal of Monetary Economics 54 (2007), 100-121.

[6] Canova, Fabio and Gianni De Nicolo, "Monetary Disturbances Matter for Business Fluctuations in the G-7", Journal of Monetary Economics 49 (2002), 1131-1159.

[7] Calvo, Guillermo, "Staggered Prices in a Utility-maximizing Framework", Journal of Monetary Economics 12 (1983), 383-398.

[8] Christiano, Lawrence J., Martin Eichenbaum and Charles L. Evans, "Nominal

Rigidities and the Dynamic Effects of a Shock to Monetary Policy", Journal of Political Economy 113 (2005), 1-45.

[9] Christiano, Lawrence J., Martin Eichenbaum and Sergio Rebelo, "When Is the Government Spending Multiplier Large?", Journal of Political Economy 119 (2011), 78–121.

[10] Cover, James, "Asymmetric Effects of Positive and Negative Money-supply Shocks" Quarterly Journal of Economics 107 (1992), 1261-1282.

[11] Faust, Jon, "The Robustness of Identified VAR Conclusions About Money", Carnegie-Rochester conference series on public policy 49 (1998), 207-244.

[12] Garcia, Rene and Huntley Schalle, "Are the Effects of Monetary Policy Asymmetric?", Economic Inquiry 40 (2002), 102-119

[13] Justiniano, Alejandro, Giorgio E.Primiceri and Andrea Tambalotti, "Investment shocks and business cycles", Journal of Monetary Economics 57 (2010), 132-145.

[14] Klenow, Peter J. and Oleksiy Kryvtsov, "State-dependent or Time-dependent Pricing: Does It Matter for Recent U.S. Inflation?", Quarterly Journal of Economics 123 (2008), 863-904.

[15] Koop, Gary, Hashem Pesaran and Simon Potter, "Impulse Response Analysis in Nonlinear Multivariate Models", Journal of Econometrics 74 (1996), 119-147.

[16] Kuester, Keith, "Real price and wage rigidities with matching frictions", Journal of Monetary Economics 57 (2010), 466-477.

[17] Lo, Ming Chien and Jeremy Piger, "Is the Response of Output to Monetary Policy Asymmetric? Evidence from a Regime-Switching Coefficients Model" Journal of Money, Credit and Banking 37 (2005), 865-886.

[18] Peersman, Gert and Frank Smets, "Are the Effects of Monetary Policy in the Euro Area Greater in Recessions than in Booms?", Working Paper Series 052 (2001), European Central Bank.

[19] Rotemberg, Julio. J., "Sticky prices in the united states", Journal of Political Economy 90 (1982), 1187–1211.

[20] Sims, Eric, and Jonathan Wolff, "The state-dependent effects of tax shocks", European Economic Review 107 (2018), 57-85.

[21] Schmitt-Grohe, Stephanie and Martin Uribe, "Optimal Fiscal and Monetary Policy in a Medium-Scale Macroeconomic Model", NBER Macroeconomics Annual 20 (2005), 383–425.

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

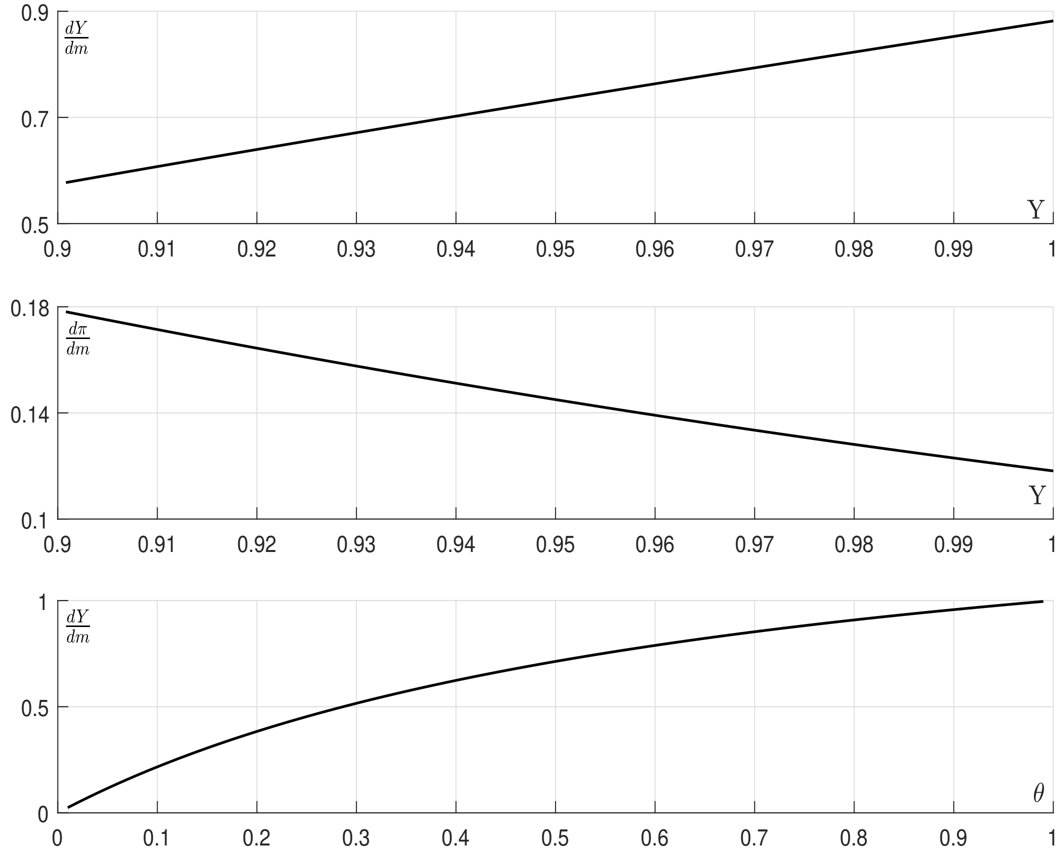
[23] Thoma, Mark, "Subsample Instability and Asymmetries in Money-income Causality", Journal of Econometrics 64 (1994), 279-306.

[24] Tenreyro, Silvana and Gregory Thwaites, "Pushing on a String: US Monetary Policy is Less Powerful in Recessions", American Economic Journal: Macroeconomics 8 (2016), 43-74.

[25] Vavra, Joseph, "Inflation Dynamics and Time-varying Volatility: New Evidence and an Ss Interpretation", Quarterly Journal of Economics 129 (2014), 215-258.

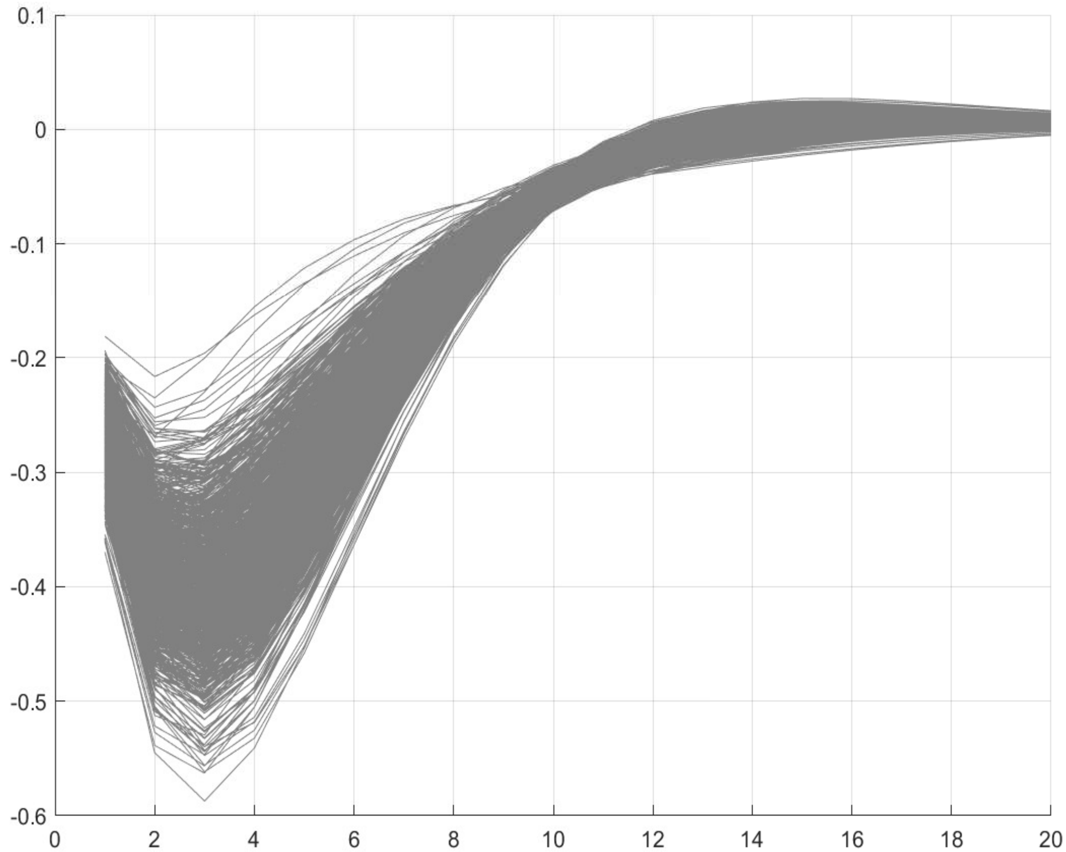
[26] Weise, Charles, "The Asymmetric Effects of Monetary Policy: A Nonlinear Vector Autoregression Approach", Journal of Money, Credit and Banking 31 (1999), 85-108.

Figure 1. State-dependent Effects of Policy Shifts in the Static Model



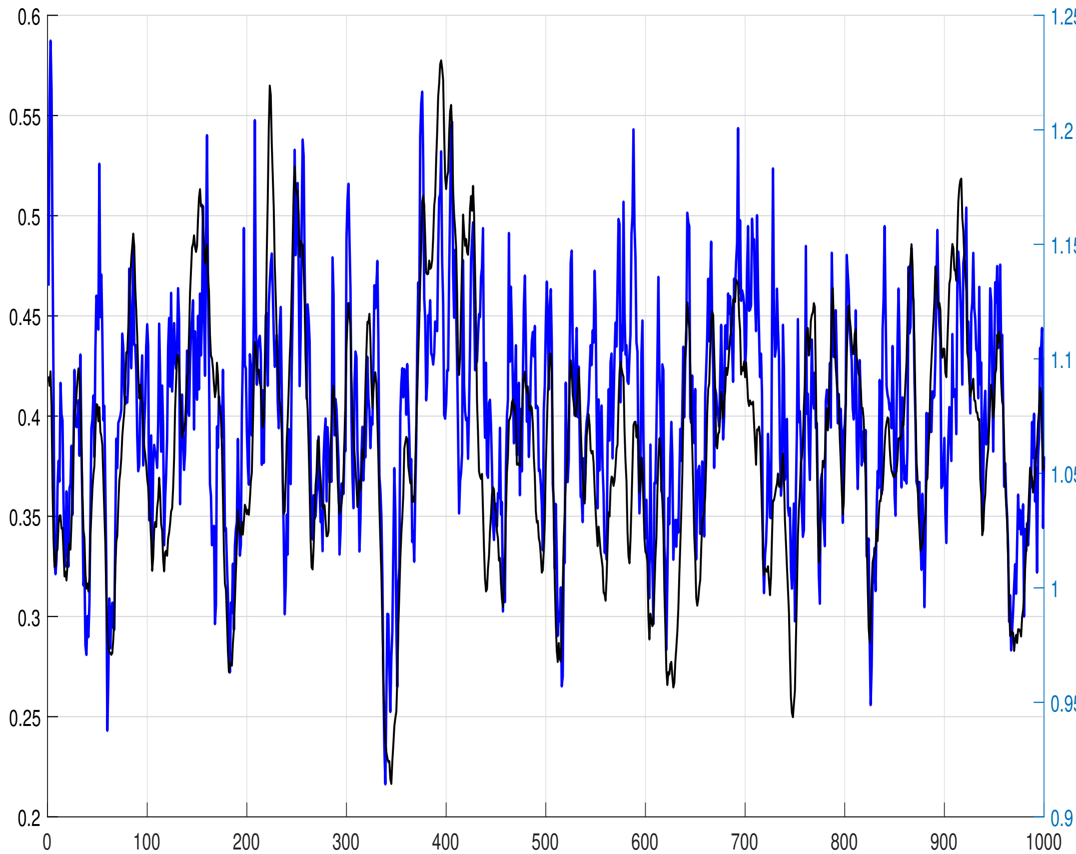
Notes: The first and the second panels plot output and inflation responses to policy shocks for different values of output. In these calculations, I fix $\beta = 1$, $\theta = 0.75$, $\phi = 1.5$, $\epsilon = 6$.
The third panel plots output response to policy shocks for different values of θ. In these calculations, $\theta \in [0.01; 0.99]$ and $m = 1$.

Figure 2. Output Impulse Responses



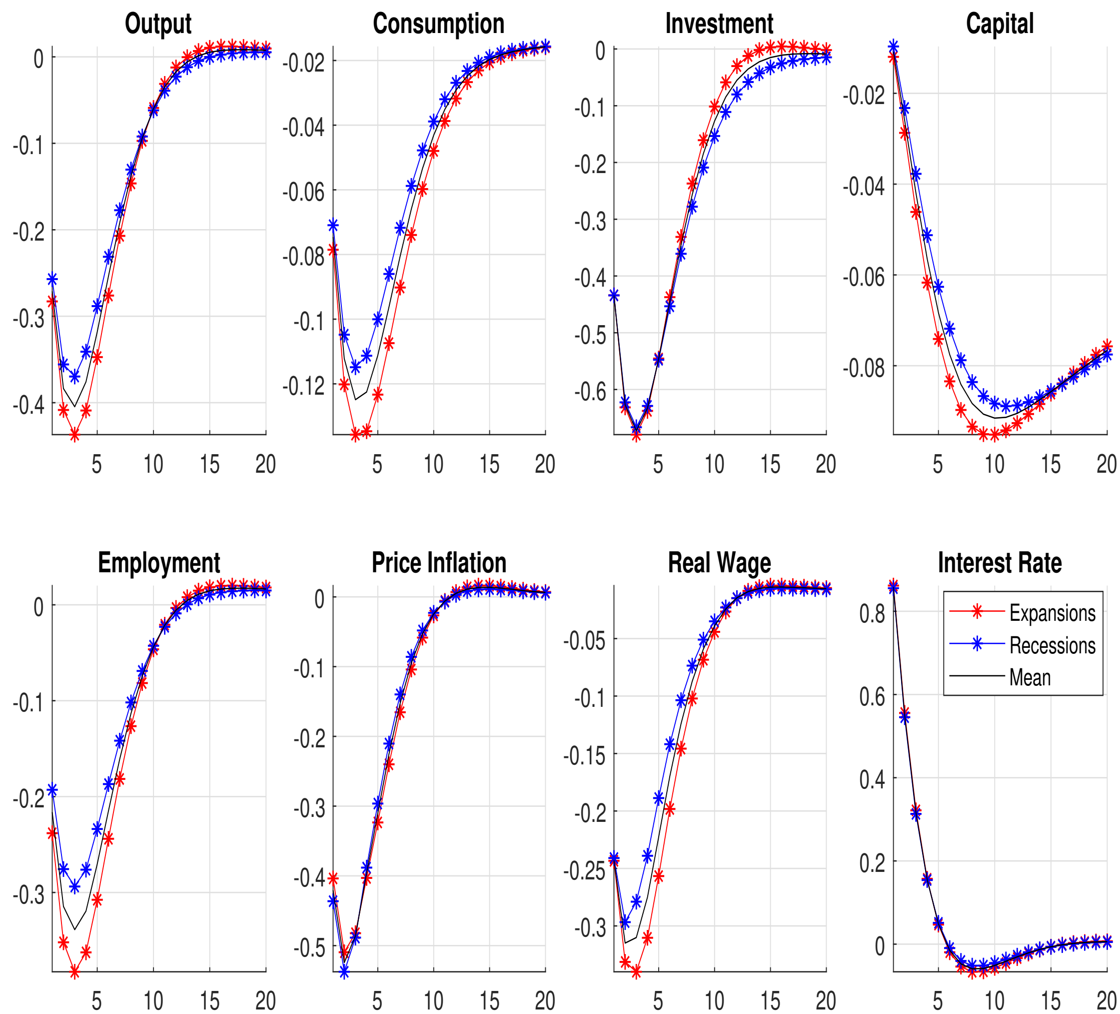
Notes: The figure plots the impulse response functions from each of the 1000 simulated states. The responses are in percentage deviations from the ergodic mean.

Figure 3. Output Response Across the States



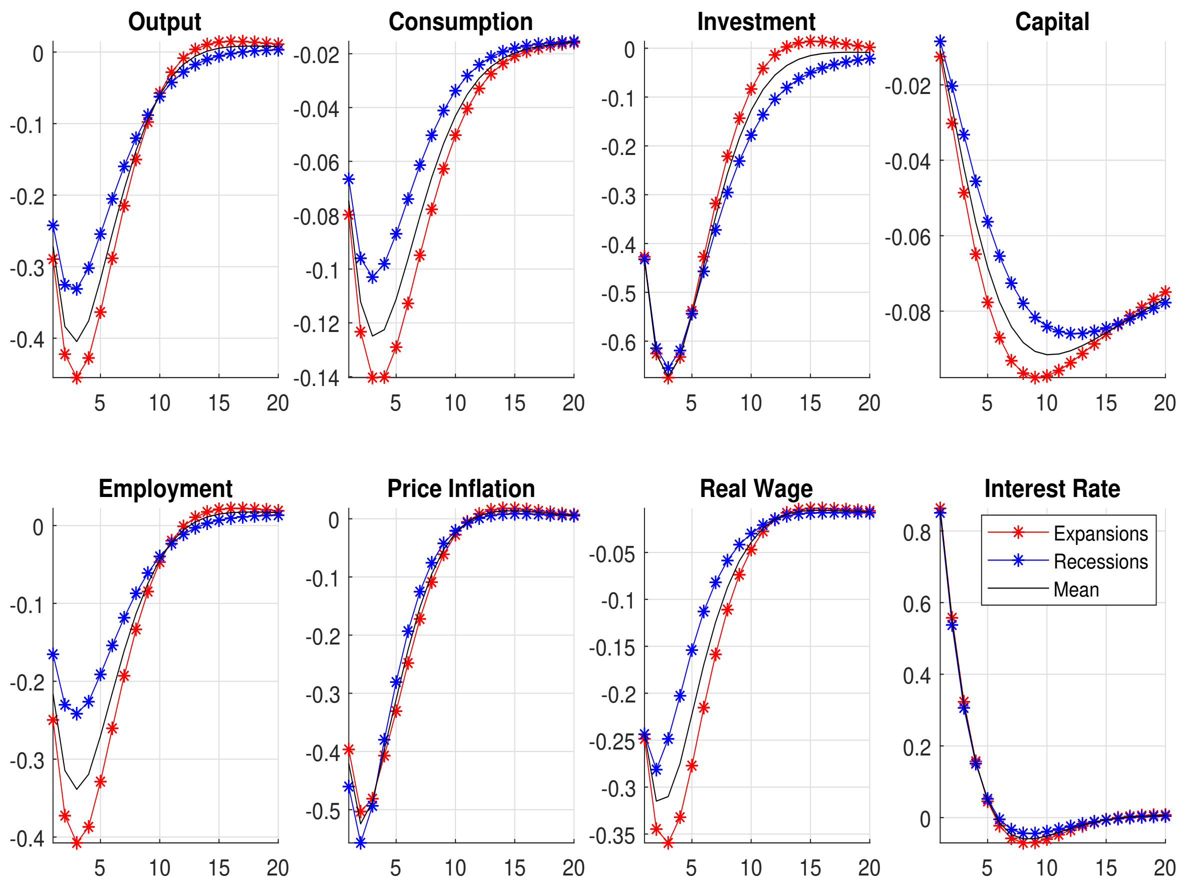
Notes: The figure plots the simulated series of output (right vertical axis) and the absolute values of maximum response of output for each state (left axis).

Figure 4. State-Dependent Effects of Policy Shocks: Recessions versus Expansions



Notes: The figure plots the average impulse response functions across the recessionary (blue lines) and expansionary (red lines) states. It also shows the responses computed at the ergodic mean of the model (black lines). All entries are in percent deviations from corresponding mean values. For inflation and the interest rate, entries are in annualized percentage points.

Figure 5. State-Dependent Effects of Policy Shocks: Deep Recessions versus Booms



Notes: The figure is similar to Figure 4 but plots the average response functions across the deep recessions and booms.

Table 1. Calibrated Parameters

Parameter	Description	Value/Target
β	Time discount factor	0.99
δ	Depreciation rate	0.025
α	Share of Capital	$\frac{1}{3}$
ϕ_0	Linear term utilization cost	$\frac{1}{\beta} + 1 - \delta$
ϕ_1	Quadratic term utilization cost	0.01
π	Inflation target	0

Note: This table reports the values of calibrated parameters in the baseline DSGE model.

Table 2. Parameter Estimates

Parameter	Description	Prior			Posterior		
		Dist	Mean	SD	Mean	90th Percentile	
h	Habit formation	B	0.75	0.05	0.72	0.66	0.78
σ	Utility curvature	N	2.00	0.25	2.48	2.13	2.82
γ	Utility curvature	B	0.30	0.05	0.29	0.22	0.37
τ	Inv. adj. cost	N	4.00	0.5	4.26	3.54	4.98
ξ_w	Wage indexation	B	0.50	0.05	0.49	0.41	0.57
ξ_p	Price indexation	B	0.50	0.05	0.43	0.41	0.57
θ_w	Wage stickiness	B	0.75	0.05	0.79	0.76	0.83
θ_p	Price stickiness	B	0.75	0.05	0.76	0.73	0.80
ϵ_w	Labor substitutability	N	21.00	1.00	21.10	19.40	22.63
ϵ_p	Product substitutability	N	21.00	1.00	20.42	19.30	23.61
ϕ_π	Response to inflation	N	1.50	0.05	1.51	1.44	1.60
ϕ_Y	Response to GDP growth	N	0.12	0.025	0.14	0.10	0.18
ρ_i	Interest rate persistence	B	0.80	0.05	0.79	0.76	0.82
ρ_A	Productivity persistence	B	0.80	0.05	0.95	0.93	0.97
ρ_Z	MEI persistence	B	0.80	0.05	0.87	0.83	0.91
ρ_μ	Preference persistence	B	0.80	0.05	0.84	0.76	0.90
ρ_{v_w}	Wage markup persistence	B	0.80	0.05	0.67	0.58	0.76
ρ_{v_p}	Price markup persistence	B	0.80	0.05	0.82	0.76	0.89
$100 * \sigma_i$	SD monetary policy shock	IG	0.50	0.20	0.16	0.14	0.18
$100 * \sigma_A$	SD Productivity shock	IG	0.50	0.20	0.53	0.47	0.59
$100 * \sigma_Z$	SD MEI shock	IG	0.50	0.20	2.85	2.35	3.38
$100 * \sigma_\mu$	SD preference shock	IG	0.50	0.20	2.04	1.32	2.70
$100 * \sigma_{v_w}$	SD wage markup shock	IG	0.50	0.20	4.00	2.88	5.03
$100 * \sigma_{v_p}$	SD price markup shock	IG	0.50	0.20	1.24	0.94	1.51

Notes: The table shows the estimation results of the baseline model. B stands for beta distribution, N for normal distribution, and IG stands for inverse gamma. The posterior is generated with 50000 random walk Metropolis Hastings draws with an acceptance rate of approximately 35 percent. Under posterior results, the ranges display 90 percent confidence intervals.

Table 3. The Impact of Policy Shocks in Recessions versus Expansions

	Recessions		Ergodic Mean		Expansions	
	Impact	Max	Impact	Max	Impact	Max
Output	0.26	0.37	0.27	0.40	0.28	0.44
Consumption	0.07	0.11	0.07	0.12	0.08	0.14
Investment	0.43	0.67	0.40	0.67	0.43	0.68
Employment	0.19	0.29	0.22	0.34	0.24	0.38
Inflation	0.44	0.54	0.42	0.52	0.40	0.50

Notes: The table shows the average impact responses and the average maximum responses of the selected variables to a 25 basis point contractionary policy shock. All entries are in percent deviations from corresponding mean values. For inflation rate, entries are in annualized percentage points. The values are in absolute terms.

Table 4. The Impact of Policy Shocks in Deep Recessions versus Booms

	Deep Recessions		Ergodic Mean		Booms	
	Impact	Max	Impact	Max	Impact	Max
Output	0.24	0.33	0.27	0.40	0.29	0.46
Consumption	0.06	0.10	0.07	0.12	0.08	0.15
Investment	0.43	0.65	0.40	0.67	0.43	0.68
Employment	0.17	0.24	0.22	0.34	0.25	0.41
Inflation	0.46	0.54	0.42	0.52	0.40	0.50

Notes: This table is similar to Table 3 but reports the average impact responses in deep recessions and booms.

Table 5. Sources of State-Dependence

	Recessions					
	Baseline	$h = 0.1$	$\phi_1 = 10$	$\tau = 10$	$\theta_w = 0.1$	$\theta_p = 0.1$
Output	0.37	1.0	0.21	0.27	0.36	0.12
Consumption	0.11	0.75	0.11	0.11	0.09	0.05
Investment	0.67	0.66	0.56	0.33	0.52	0.25
Employment	0.29	0.99	0.28	0.21	0.20	0.13
Inflation	0.54	0.60	0.61	0.48	0.69	1.11

	Expansions					
	Baseline	$h = 0.1$	$\phi_1 = 10$	$\tau = 10$	$\theta_w = 0.1$	$\theta_p = 0.1$
Output	0.44	1.02	0.22	0.30	0.43	0.13
Consumption	0.14	0.79	0.12	0.12	0.11	0.05
Investment	0.68	0.65	0.57	0.33	0.54	0.25
Employment	0.38	1.02	0.31	0.25	0.30	0.14
Inflation	0.50	0.59	0.60	0.46	0.61	1.07

Notes: The table shows the average maximum responses of the selected variables to a 25 basis point contractionary policy shock under the baseline and alternative parameterizations. All entries are in percentage deviations from corresponding mean values. For inflation rate, the entries are in annualized percentage points. The values are in absolute terms.

Table 6. The Impact of Policy Shocks in Recessions versus Expansions: Rotemberg model

	Recessions		Ergodic Mean		Expansions	
	Impact	Max	Impact	Max	Impact	Max
Output	0.17	0.37	0.22	0.41	0.26	0.46
Consumption	0.07	0.12	0.07	0.13	0.08	0.14
Investment	0.46	0.72	0.45	0.71	0.44	0.69
Employment	0.11	0.31	0.16	0.35	0.21	0.39
Inflation	0.37	0.48	0.38	0.48	0.39	0.50

Notes: The table shows the average impact responses and the average maximum responses of the selected variables to a 25 basis point contractionary policy shock. All entries are in percent deviations from corresponding mean values. For inflation rate, entries are in annualized percentage points. The values are in absolute terms.