Risk Premium Shocks and the Zero Bound on Nominal Interest Rates*

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Abstract

There appears to be a disconnect between the importance of the zero bound on nominal interest rates in the real-world and predictions from quantitative DSGE models. Recent economic events have reinforced the relevance of the zero bound for monetary policy whereas quantitative models suggest that the zero bound does not constrain (optimal) monetary policy. This paper attempts to shed some light on this disconnect by studying a broader range of shocks within a standard DSGE model. Without denying the possibility of other factors, we find that risk premium shocks are key to building quantitative models where the zero bound is relevant for monetary policy design. The risk premium mechanism operates by increasing the spread between the rates of return on private capital and risk-free government bonds. Other common shocks, such as aggregate productivity, investment-specific productivity, government spending and money demand shocks, are unable to push nominal bond rates close to zero as the same risk premium spread mechanism is not at play. We also consider the efficacy of price-level targeting in the face of risk premium shocks since some researchers have argued that price-level targeting may be a way to reduce the probability of hitting the zero bound.

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1 Introduction

Recent economic events have highlighted the importance of the zero bound on nominal interest rates for monetary policy. Indeed, a number of central banks have lowered their policy interest rates to record lows. By the second quarter of 2009, policy interest rates will have fallen below one percent in Canada, England, the Euro Area, Japan, Sweden, Switzerland and the United States. From a theoretical perspective, Eggertsson and Woodford (2003a) show, in the context of a two-equation macroeconomic model, that the zero bound has to be taken into account when formulating monetary policy because hitting the bound may, in principle, lead to large and protracted losses in output.[1]

In contrast to real-world events, quantitative DSGE models are often unable to find an important role for the zero nominal interest rate bound when the monetary authority (optimally) focuses on stabilizing the price level.[2] Christiano (2004) extends the analysis of Eggertsson and Woodford to include capital and government spending, and finds that the zero bound is not likely to bind. Schmitt-Grohe and Uribe (2007) study, *inter alias*, the zero bound problem in a medium-scale DSGE model with distortionary taxes and three shocks: aggregate productivity, investment-specific productivity, and government spending shocks. The model is calibrated to U.S. data and shows that under the optimal policy (which does not take the zero-bound in account), the probability of the nominal interest rate approaching the zero bound is practically nil. This conclusion arises despite the fact that optimal average inflation rate in the model is slightly negative. Given the unsettled nature of this literature, Christiano (2004) argues that additional research allowing for a broader range of shocks may improve our understanding of the factors that occasionally force central banks to face the zero bound on nominal interest rates. This is the starting point for our paper.

In this paper, we construct a quantitative DSGE model that appears capable of capturing the relevance of the zero bound on nominal interest rates. Our model is a calibrated general-equilibrium model along the lines of Christiano (2004) and Schmitt-Grohe and Uribe (2007) but we consider a broader range of economic shocks.[3] Our

[1] Their results, however, are based on the application of a non-structural shock so it is not straightforward to isolate the source of the shock or its empirical magnitude.

[2] These types of studies often focus on a monetary policy that attains complete price-level stability. As Woodford (2003) and Goodfriend and King (1997) show such a policy of "price-stability" is robustly optimal or near-optimal in sticky-price models with various shocks and frictions. Henceforth, we will refer to such a policy where inflation is kept constant at zero at all times as a "zero-inflation policy".

[3] There is a related literature examining the real implications of the zero bound in relation to targeted rates of inflation and posited monetary policy rules. Examples include Fuhrer and Madigan

results indicate that even under a zero inflation policy, historically-measured aggregate shocks - such as productivity, investment-specific productivity, government spending and money demand shocks - do not drive the nominal interest rate to its zero bound. The only shock in our analysis that forces the central bank to face the zero bound is a risk premium shock (perturbations that widen the spread between the rate of return on private capital and the risk-free rate).[4] Indeed, even conservatively measured risk premium shocks (such as those reported in Campello, Chen and Zhang 2008) are capable of driving the risk-free nominal interest rate to zero. As such, our analysis focuses only on the exogenous component of the risk premium. We do so for two reasons. First, it greatly simplifies the solution and computation of our already non-linear model. Second, previous empirical finance studies (e.g. Collin-Dufresne, Goldstein and Martin 2001, and Huang and Huang 2003) estimated that only a modest fraction (20 to 30 percent) of total risk premium can be explained by observable risk characteristics of individual firms. In an important sense, our use of risk premium shocks is similar to the uncovered interest parity condition shocks often introduced in the literature on new open economy macroeconomics (see, e.g., Bergin 2006). In particular, both types of shocks appear to be important in allowing a DSGE model to track the data and are known to be important from reduced-form econometric analysis, but are not well-understood from a theoretical perspective.

Intuition for the "special" role of risk premium shocks can be gained from the observation that these shocks change the spread between the expected rate of return on capital and the risk-free rate. This implies that either the expected rate of return on capital must increase, or the risk-free rate must fall, or both, to accommodate the higher risk premium. For a wide range of plausible parameter configurations, much of the increase in the risk premium is accommodated by a fall in the risk-free rate, thus increasing the probability that the zero bound may bind. In contrast, the other aggregate shocks we examine do not move the rate of return on capital and the risk-free rate in opposite directions. Instead, both expected returns move in the same direction

(1997), Reifschneider and Williams (2000), Coenen, Orphanides and Wieland (2004) and Wolman (2005). The current work, in contrast, focuses on monetary policy that has been shown to be optimal across a number of related sticky-price models. Our paper also does not address questions about optimal monetary policy in the presence of zero nominal interest rate bound (see, e.g., Rotemberg and Woodford 1998, Eggertsson and Woodford 2003b, and Adam and Billi 2006, 2007).

[4] In a similar vein, Curdia and Woodford (2009) have recently extended a New Keynesian model to allow for an interest rate spread. In their case, they study the role of a spread between the interest rate available to borrowers and savers and find, as in our work, fluctuations in the spread to be important for understanding key economic relationships.

and by roughly the same proportion so the zero bound can only be reached with extreme realizations of these shocks.

Interestingly, our results are broadly consistent with past episodes where central banks hit or approached the zero nominal interest rate bound. Nominal policy interest rates in Japan since 1999, the United States and Switzerland in 2003-04 and many developed countries in 2008-09 hit or hovered above zero and these occurrences were preceded by significant turmoil in financial markets. More specifically, the collapse of an asset price "bubble" in the early 1990s, the rapid decline in the valuation of high technology related assets in 2000 and the breakdown of the sub-prime mortgage market in 2008 lead to bouts of zero or near zero policy rates as our model would predict.[5]

The remainder of the paper is organized as follows. Section 2 outlines the main features of our model and Section 3 describes its calibration. Section 4 presents our main result and Section 5 gives some sense of the robustness of the key result. Section 6 presents results under a price-level targeting rule. This section is motivated by the results reported in Wolman (2005) and Eggertsson and Woodford (2003b) that show price-level targeting rules are effective in reducing the probability of hitting the zero bound. Concluding remarks are provided in Section 7.

2 Model

The model is a standard real-business-cycle model extended to include sticky nominal prices, money and nominal government bonds. In the model, infinitely-lived households: (i) maximize a utility function which depends on consumption, money and leisure; (ii) decide on the amount of capital to accumulate given capital adjustment costs; and (iii) allocate the remaining wealth across fiat money and a risk-free government bond. Intermediate good firms produce differentiated goods by: (i) deciding on labour and capital inputs; and (ii) setting prices according to a Calvo (1983) specification. A representative final good producer combines intermediate goods into a final consumption good. The government finances exogenous government spending with lump sum taxes. And finally, a monetary authority sets the short-term interest rates, and allows the money supply be determined by the demand for real balances.

[5]Bank of Japan ex-Deputy Governor Ueda (2005), for instance, writes that many of the monetary policy measures adopted by Bank of Japan during its zero interest rate policy era were aimed at mitigating financial sector problems. Ueda goes on to say that the Bank of Japan was concerned about the rising risk premiums, and attempted to counteract them by lowering the "risk-free" nominal rate.

Lump-sum taxes are used to finance changes in the money stock. In the forthcoming formal description of the model, we focus on key relationships concerning investment, the capital stock, its marginal product, the risk-free nominal interest rate and a risk premium term.[6]

2.1 Households

The representative household maximizes expected utility

$$\max E_0 \sum_{t=0}^{\infty} \beta^t \left[\frac{\gamma}{\gamma - 1} \log \left(C_t^{\frac{\gamma-1}{\gamma}} + u_t^{\frac{1}{\gamma}} \left(\frac{M_t}{P_t} \right)^{\frac{\gamma-1}{\gamma}} \right) + \eta \log (1 - h_t) \right],$$

where C_t is consumption, M_t represents nominal balances, P_t is the price level, and h_t is hours worked. Total hours available to the household in each period are normalized to one. The parameters β, γ, and η represent a discount factor, elasticity of substitution between consumption and real balances, and the weight on leisure in the utility function, respectively. The utility function also contains a money demand shock, u_t, of the form

$$\log (u_t) = (1 - \rho_u) \log \overline{u} + \rho_u \log (u_{t-1}) + \varepsilon_{ut}; \quad \rho_u \in (-1, 1) \text{ and } \varepsilon_{ut} \backsim iid(0, \sigma_u^2).$$

The budget constraint is given by

$$\begin{aligned} & C_t + I_t + CAC_t + \frac{B_t}{P_t} \frac{1}{R_t} + \frac{M_t}{P_t} \\ \leq \; & W_t h_t + (q_t - \tau_{t-1}) \frac{P_t^k}{P_t} K_{t-1} + \frac{B_{t-1}}{P_{t-1}} \frac{1}{\pi_t} + \frac{M_{t-1}}{P_{t-1}} \frac{1}{\pi_t} + T_t. \end{aligned} \tag{1}$$

where I_t is investment, B_t represents a one-period risk-free nominal bond, R_t is the gross nominal interest rate on the risk-free bond, W_t is the real wage rate, K_{t-1} is the capital stock from the previous period, π_t is the gross rate of inflation defined as P_t/P_{t-1}, P_t^k/P_t is the relative price of capital, and T_t is a composite term that contains profits, lump-sum taxes, and monetary injections $(M_t - M_{t-1})/P_t$. The term q_t is the gross return on capital which includes the return to households and a risk premium denoted by τ_{t-1}, and CAC_t represents a capital adjustment cost which is specified as

$$CAC_t = \frac{\varphi}{2} \left(\frac{K_t}{K_{t-1}} - \gamma_k \right)^2 \frac{K_{t-1}}{X_t},$$

[6] The full system of detrended equations is provided in Appendix "B".

The parameter γ_k is the long-run average growth rate of the capital stock, φ is a positive parameter and X_t is investment-specific technology. Investment increases the household's stock of capital according to $K_t = (1-\delta)K_{t-1} + X_t I_t$ where $\delta \in (0,1)$ is the depreciation rate of capital.

As mentioned above, the gross return on capital, q_t, the risk-free interest are, R_t, and the risk premium, τ_t, will be important components of the upcoming results so we focus specifically on two first-order conditions that may help us understand the role these variables play in our results:

$$\frac{\Lambda_t}{R_t} = \beta E_t \left(\frac{\Lambda_{t+1}}{\pi_{t+1}} \right), \tag{2}$$

$$\frac{\Lambda_t}{X_t} \left[1 + \varphi \left(\frac{K_t}{K_{t-1}} - \gamma_k \right) \right] = \beta E_t \left\{ \frac{\Lambda_{t+1}}{X_{t+1}} \left[1 - \delta + q_{t+1} - \tau_t + \frac{\varphi}{2} \left(\left(\frac{K_{t+1}}{K_t} \right)^2 - \gamma_k^2 \right) \right] \right\}, \tag{3}$$

where Λ_t is the Lagrange multiplier associated with the period-t budget constraint.

It is useful to note that when we set $\varphi = 0$, assume full capital depreciation and ignore uncertainty, we can rewrite equation (3) as

$$\frac{R_t}{\pi_{t+1}} = \frac{X_t}{X_{t+1}} (q_{t+1} - \tau_t). \tag{4}$$

Given that X_t is a persistent technology shock, the ratio X_t/X_{t+1} is roughly constant and close to one. Equation (4) says that the risk premium τ_t is approximately equal to the spread between the marginal product of capital and the real interest rate. This implies that innovations in the risk premium will have first-order effects on the real interest rate or the marginal product of capital, or both. Further, if the inflation rate is held constant then all movements in the real interest rate will be reflected in one-to-one movements of the nominal risk-free rate.

2.2 Intermediate and final good producers

The final good Y_t is produced by combining a continuum of intermediate goods $Y_t(i)$ for $i \in [0,1]$ that are imperfect substitutes according to a constant returns to scale technology given by

$$Y_t = \left[\int_0^1 Y_t(i)^{\frac{\theta-1}{\theta}} di \right]^{\frac{\theta}{\theta-1}}, \tag{5}$$

where $\theta > 1$ is the elasticity of substitution between types of differentiated intermediate goods. The final goods sector is perfectly competitive so profit maximization leads to the following input-demand function for each intermediate good i

$$Y_t(i) = \left[\frac{P_t(i)}{P_t}\right]^{-\theta} Y_t. \quad (6)$$

which specifies economy-wide demand for good i as a function of its relative price, $P_t(i)/P_t$, and aggregate output, Y_t.

Each intermediate good i firm produces $Y_t(i)$ units given the following production function

$$Y_t(i) = A_t K_t(i)^{1-\alpha} H_t(i)^{\alpha} \quad (7)$$

where $K_t(i)$ and $H_t(i)$ are capital input and labour hours input, and the aggregate productivity level A_t is given by

$$\log\left(\frac{A_t}{A_{t-1}}\right) = g_a + \varepsilon_{at}, \quad \varepsilon_{at} \sim N(0, \sigma_{\varepsilon_a}), \quad (8)$$

as in Fisher (2006).

In order to introduce nominal price stickiness into the model, producers of the intermediate goods are assumed to set prices according Calvo (1983) style contracts. Specifically, firms have a constant probability (d) that their price set in time t will still be in force at time $t+1$. When the ith intermediate good firm is allowed to re-optimize its price in period t, it sets its price to maximize the discounted sum of its expected future profits.

2.3 Fiscal and Monetary Authorities

We assume government expenditures, G_t, are financed by lump-sum taxes[7] on households and that a fraction of government expenditures in GDP, $g_t = G_t/Y_t$, follows a stationary AR(1) process:[8]

$$g_t = \left(1 - \rho_g\right)\bar{g} + \rho_g g_{t-1} + \varepsilon_{g,t}, \text{ where } \varepsilon_{g,t} \sim N(0, \sigma_{\varepsilon_g}).$$

[7] Time-varying capital income taxes can have a similar effect as the risk-premium shocks analyzed in this paper. Such taxes would create a time-varying spread between the return on capital, which is taxed, and the risk-free rate, which is tax exempt.

[8] With this process, the fraction is not constrained to lie between zero and one. It is, however, never a problem in the simulations and, thus, we retain this assumption for simplicity.

For monetary policy, we follow Christiano (2004) in focusing on a very simple monetary policy which keeps net inflation precisely at zero in all periods, $\pi_t - 1 = 0 \ \forall \ t$. This policy has been quite prominent in the literature on optimal monetary policy with sticky nominal prices. King and Wolman (1999), for example, show in a sticky-price model that a monetary policy of keeping the price level perfectly constant in all periods is a close approximation to optimal monetary policy. The main reason for this finding is that a constant price-level effectively negates relative price distortion, and induces the economy to behave as a flexible-price economy. Khan, King and Wolman (2003) add a transaction demand for money to a sticky-price model, and find that optimal monetary policy can sometimes imply a very mild deflation with very small fluctuations of the price level around a declining trend. The mild deflation arises as an optimal compromise between price stability, which minimizes relative price distortions, and the Friedman rule, which eliminates the cost of money holdings. Overall, Khan, King and Wolman (2003) suggest that eliminating price distortions is an important concern and the role of optimal monetary policy, to a first approximation, is to stabilize the price level. Goodfriend and King (2001) show that the near-optimality of price-level stabilization is likely robust across a wide variety of sticky-price models. Siu (2004) and Schmitt-Grohe and Uribe (2004) derive optimal fiscal and monetary policy under sticky prices and confirm that even small degrees of price rigidity imply very little volatility of optimal inflation. Finally, Schmitt-Grohe and Uribe (2005) reach a similar conclusion in a much larger model with various real and nominal frictions: the optimal inflation rate is nearly constant over time, albeit slightly negative as in Khan, King and Wolman (2003).[9]

2.4 Aggregation

We assume the presence of a rental market for capital that allows firms to rent their desired level of capital input. All firms have the same capital-to-labor ratio and real marginal cost, $\psi_t(i)$. Also, firms that change their price in the same period choose the same price $P_t^*(i)$. As a result, we can drop the (i) argument for real marginal cost, ψ_t, and newly chosen price, P_t^*. Integrating over the demand function (6) we obtain the

[9] In this paper we do not study optimal monetary policy in the presence risk premium shocks. We plan on undertaking such a study in future work.

following aggregate resource constraint:

$$Y_t^s = \left(C_t + \frac{K_t - (1-\delta)K_{t-1}}{X_t} + G_t + CAC_t \right) S_t \tag{9}$$

where

$$S_t \equiv \int_0^1 \left(\frac{P_t(i)}{P_t} \right)^{-\theta} di, \tag{10}$$

which under Calvo pricing has the law of motion:

$$S_t = (1-d) p_t^{*-\theta} + d{\pi_t}^{\theta} S_{t-1}. \tag{11}$$

Finally aggregate supply, Y_t^s, is given by

$$Y_t^s = A_t K_{t-1}^{1-\alpha} {h_t}^{\alpha} \tag{12}$$

where K_{t-1} and h_t are the aggregate capital stock and aggregate hours worked, respectively.

3 Calibration

We start this section with a brief overview of our calibration strategy. We measure aggregate shocks from the data, namely: (i) risk premium shocks as measured by Campello, Chen and Zhang (2008) from micro data on corporate bond spreads of US corporations; (ii) aggregate productivity shocks derived from a TFP series obtained by fitting a Cobb-Douglas production function to aggregate capital, labour hours and real GDP; (iii) investment-specific shocks as estimated in Fisher (2006); (iv) money demand shocks, estimated from movements in the monetary base; and (v) government spending shocks calculated from the NIPA data.

The remaining parameters are calibrated by matching average values (first moments) of observable data, except for the capital adjustment cost parameter, φ. In order to calibrate φ, we need second moments from the model which in turn require us to specify a model of monetary policy that is congruent with the historical data. As such, we posit a forward-looking Taylor rule of the form

$$\log R_t = (1-\rho_R) \left(\log \bar{R} + \rho_\pi E_t \log \left(\frac{\pi_{t+1}}{\bar{\pi}} \right) + \rho_y \log \left(\frac{y_t}{\bar{y}} \right) \right) + \rho_R \log R_{t-1}, \tag{13}$$

which has been found by Taylor (1993), Clarida, Gali and Gertler (1999), Orphanides (2003) and others to capture well broad movements in Federal Reserve policy interest rates. The terms $\bar{R}$, $\bar{\pi}$, $\bar{y}$ are the steady-state values of R_t, π_t, and the de-trended output, y_t. The parameters, ρ_R, ρ_π, and ρ_y, that govern the response of the monetary authority to deviations from the steady state, and the capital adjustment coefficient φ, are calibrated by stochastically simulating the model and matching a set of second moments from the data.

The following three subsections provide greater detail on our calibration exercise. Unless otherwise noted, we use the sample period 1974Q1 to 1998Q1 This data limitation is owing strictly to the availability of risk premium data and our objective of maintaining a consistent sample period across the calibrations. More details on data sources and data transformations are available in Appendix "A".

An alternative approach to parameter measurement is, of course, estimation. Preliminary work, however, indicated that the relatively large dimensionality of the model and inherent nonlinearity associated with the zero bound made estimation extremely difficult. As such, we opt to use calibration as a practical method to measure parameter values.

3.1 Calibrating aggregate shocks

We start by constructing a measure of risk premium shocks using ex-ante equity risk premium data constructed by Campello, Chen and Zhang (2008) for the 1974Q1 to 1998Q1 sample period.[10] These authors exploit information on observable corporate bond spreads (relative to government bonds of the same maturity structure) to make inferences about the unobservable ex-ante risk premium on common stock of the same corporation. In estimating those risk premiums, the authors control for taxes and grade-specific default rates, as well as other observable determinants of the default risk such as leverage. We take the component remaining after accounting for these observable, firm-specific risk characteristics as our risk premium shock. In our model, an exogenous risk premium shock drives a time-varying wedge between the expected real return on capital and expected real return on risk-free nominal bonds so the residual risk premium component reported in Campello, Chen and Zhang (2008) appears to be a reasonable

[10] The dataset was downloaded from Lu Zhang's website in September 2008. The data are monthly so we converted them into quarterly data (to match the frequency of the other variables) by simply taking the average over the three months of each quarter. Moreover, the risk premiums are reported on an annualized basis, so we also divided the values by four.

empirical counterpart.[11] Figure 1 plots two of the series constructed by Campello, Chen and Zhang (2008). The series are for BBB and AAA/AA corporations. It is clear from the figure that the two series are quite different especially at the beginning of the sample period, where the BBB series is much more volatile than AAA/AA series. We chose BBB series as our benchmark risk premium shock, but we also report results for the AAA/AA series in the sensitivity analysis section.[12] To operationalize the benchmark shock, we estimate a simple AR(1) process from the equity premium series of the BBB grade corporations and obtain the following stochastic process:

$$\tau_t = (1 - 0.84) * 0.016 + 0.84 * \tau_{t-1} + \varepsilon_t^\tau, \quad \text{where } \varepsilon_t^\tau \sim N(0, 0.0079^2).$$

This stochastic process is the benchmark risk premium shock in our model.

Next we calibrate the stochastic processes for the aggregate and investment-specific productivities. Following Fisher (2006) we assume that both productivity shocks follow a similar process with stochastic trends:

$$\log\left(A_t/A_{t-1}\right) = g_a + \varepsilon_{at}, \quad \varepsilon_{at} \sim N(0, \sigma^2_{\varepsilon_a}) \tag{14}$$

$$\log\left(X_t/X_{t-1}\right) = g_x + \varepsilon_{xt}, \quad \varepsilon_{xt} \sim N(0, \sigma^2_{\varepsilon_x}) \tag{15}$$

We calibrate the drift terms g_a and g_x to match the growth rates of real per-capita GDP, and real per-capita capital stock in the data. Over the sample period, real GDP and real capital stock per working-age person grew at average rates of 0.43 and 0.72 percent per quarter, correspondingly. Inverting the derived growth rates of output $\gamma_y = \exp\left(\frac{g_a+(1-\alpha)g_x}{\alpha}\right)$ and capital $\gamma_k = \exp\left(\frac{g_a+g_x}{\alpha}\right)$, with the value of the labour share α set at 0.67, we obtain the implied average growth rates for TFP and investment-

[11] A possible alternative model would combine both the exogenous risk premium and the endogenous risk premium of Bernanke, Gertler and Gilchrist (1999). The latter serves as compensation for expected default losses. We focus on the exogenous part of the risk premium for simplicity, and because, previous empirical finance studies (e.g. Collin-Dufresne, Goldstein and Martin 2001 and Huang and Huang 2003) found that only a smaller fraction (20-30 percent) of the total risk premium can be explained by observable risk characteristics of individual firms.

[12] The other three risk premium series available from Lu Zhang's website are for A, BB, and B grade US corporations. We chose BBB grade as our benchmark because it was the median grade group. We also chose the least volatile AAA/AA series for our sensitivity analysis in order to stay on the conservative side with regard to the magnitude of the risk premium shocks.

specific technological change:[13]

$$
\begin{aligned}
g_a &= \ln\gamma_y - (1-\alpha)\ln\gamma_k = 0.0043 - \frac{1}{3}0.0072 = 0.0019, \\
g_x &= \alpha\ln\gamma_k - g_a = \ln\gamma_k - \ln\gamma_y = 0.0072 - 0.0043 = 0.0029.
\end{aligned}
$$

The standard deviation of the aggregate productivity shocks ($\sigma_{\varepsilon_a} = 0.0062$) is determined by fitting (14) to a TFP series generated from the Cobb-Douglas production function, $Y_t = A_t K_{t-1}^{1-\alpha} H_t^{\alpha}$, with aggregate real GDP, real capital and labour hours data. The standard deviation of the investment-specific productivity shocks, $\sigma_{\varepsilon_x} = 0.0055$ is set to be consistent with the results reported in Fisher (2006).[14]

In order to calibrate the money demand shock, we note that the first-order condition for real money balances is:

$$
u_t = \frac{m_t}{c_t}\left(1 - \frac{1}{R_t}\right)^{\gamma}.
$$

It follows that

$$
\begin{aligned}
\log u_t - \rho_u \log u_{t-1} &= (1-\rho_u)\log\bar{u} + \varepsilon_{ut} \\
&= \left(\log\frac{m_t}{c_t} + \gamma\log\left(1 - \frac{1}{R_t}\right)\right) - \rho_u\left(\log\frac{m_{t-1}}{c_{t-1}} + \gamma\log\left(1 - \frac{1}{R_{t-1}}\right)\right).
\end{aligned}
$$

Thus, we could, in principle, obtain values for $\log\bar{u}$, ρ_u, and σ_{ε_u} by estimating the equation

$$
\log\frac{m_t}{c_t} + \gamma\log\left(1 - \frac{1}{R_t}\right) = \rho_u\left(\log\frac{m_{t-1}}{c_{t-1}} + \gamma\log\left(1 - \frac{1}{R_{t-1}}\right)\right) + (1-\rho_u)\log\bar{u} + \varepsilon_{ut}, \tag{16}
$$

with m_t/c_t being the monetary base-to-consumption ratio, and R_t being the 90-day T-bill rate. Unfortunately, the parameters in (16) were not well identified empirically so we choose an alternative approach. We select a value for γ and then re-estimate

[13] The obtained growth rate of the investment-specific technological change g_x is consistent with the average rate of decline in the price of investment goods relative to consumption goods, which is equal to 0.0028 over the 1974Q1 to 1998Q1 period. This relative price was computed by dividing the BEA "Gross private domestic investment" price index by the "PCE" price index.

[14] Fisher estimates $\widehat{\sigma}_x = 0.01158$ before 1980 and $\widehat{\sigma}_x = 0.00325$ after 1980. His empirical model imposes very few model-specific restrictions and encompasses a broad range of models, including ours. Since our sample 1974Q1 to 1998Q1, falls across both subperiods, we set $\sigma_x = 0.0055$, the weighted average of Fisher's estimates. We conduct the sensitivity analysis with this parameter later in the paper.

the remaining parameters in equation (16) by OLS. We consider values of γ from a range identified in the literature, $[0, 0.2]$, (e.g., see Ball 2001) and then arrive at a final value, $\gamma = 0.06$, that maximizes the likelihood function. The resulting parameter values are: $\rho_u = 0.97$, $\bar{u} = 0.062$ and $\sigma_{\varepsilon_u} = 0.01$, which are similar to those estimated by maximum-likelihood methods in Dib and Christensen (2008).

Finally, we calibrate the stochastic process for the share of government consumption in GDP, g_t by fitting the AR(1) stochastic process to the observed share of government consumption in GDP. The result is

$$g_t = (1 - 0.98)\, 0.162 + 0.98 g_{t-1} + \varepsilon_{g,t}, \text{ where } \varepsilon_{g,t} \sim N(0, 0.002^2),$$

which implies $\bar{g} = 0.162$, $\rho_g = 0.98$, and $\sigma_{\varepsilon_g} = 0.002$.[15]

3.2 Static calibration

Consistent with results reported in Clarida, Gali and Gertler (1999) over roughly the same period, we set the Federal Reserve's implicit inflation objective, $\bar{\pi}$, to be 3.6 percent. Estimates of the real interest rate are measured with substantial uncertainty, but they tend to lie between two and three percent over the sample period under consideration (e.g. Laubach and Williams 2003). As such, our benchmark calibration for the real interest rate, $\bar{r}$, is 2.5, but we conduct sensitivity analysis over the two to three range. Given the benchmark value of $\bar{r}$ and the above growth rates of technology, the discount rate, $\beta = [\exp((g_a + (1 - \alpha)\, g_x)/a)]/\bar{r} = 0.998$.

Further, we set the Calvo probability parameter $d = 2/3$, consistent with the micro literature on sticky nominal prices (e.g. Bils and Klenow, 2004).[16] The elasticity of the substitution between intermediate goods, θ, the preference weight on leisure, η, and the depreciation rate, δ, are jointly determined via a non-linear search algorithm which isolates values for these parameters by matching three data moments, namely: (i) the fraction of working hours ($h = 0.25$); (ii) the average private consumption to GDP ratio ($c/y = 0.65$); and (iii) the average labour income share, 0.58, calculated from the NIPA data. The results are $\theta = 7.7$, $\eta = 2.7$ and $\delta = 0.026$.

[15] We estimate this process over the longer 1974Q1 to 2008Q2 period. After a relatively stable period from 1974, government consumption share in GDP declines steadily from 1991 to 1999 and then increases. As a result, the share appears nonstationary if one restricts one's attention to the 197Q1 to 1998Q1 period, making it difficult to fit a stationary process to the series.

[16] Variation in the value of d has little effect on the dynamics of the economy under the benchmark zero-inflation policy.

3.3 Dynamic calibration

Finally, in order to calibrate the dynamic parameters, we log-linearize the model with a forward-looking Taylor rule (as discussed above) and solve for the predicted second moments of the model. Then we use a non-linear search algorithm to find the parameter values for the capital adjustment coefficient, φ, and for Taylor rule coefficients, ρ_R, ρ_π, ρ_y, so as to match the following four moments: (i) the standard deviation of the nominal investment (inclusive of net exports and government investment) to consumption ratio in the data (0.0326); (ii) the first-order autocorrelation coefficient of the 90-day nominal treasury bill rate (0.95); (iii) the standard deviation of the 90-day nominal treasury bill rate (0.0063) and (iv) the standard deviation of the nominal labour income share (0.0092). We focus on the first moment since its value in the model is influenced primarily by the investment adjustment costs. The two moments of the risk-free rate were chosen because of our focus on the behavior of the nominal interest rate relative to zero bound. With sticky nominal prices, the standard deviation of the labour income share is sensitive to the monetary policy rule, so we chose this moment to properly match the Taylor rule.[17] The calibrated values of the parameters are $\varphi = 18.6$, $\rho_R = 0.51$, $\rho_\pi = 1.29$, and $\rho_y = 0.034$.[18] Table 1 lists the calibrated benchmark parameter values.

Before concluding, we provide an indication of how well the model matches the data by comparing moments that were not directly used for calibration. Table 2 reports standard deviations (in percent) and first-order autocorrelation coefficients for working hours, inflation, the nominal investment-to-GDP ratio, the nominal investment-to-consumption ratio, the labour share and the risk-free rate. The second and third columns of the Table report results based on US data, while the fourth and fifth columns report model-generated moments. The numbers in bold are the moments that we targeted beforehand via calibration.

[17] Note that none of our target second moments require detrending.

[18] The calibrated values of the Taylor rule coefficients are broadly in line with the range of values estimated by other researchers. Clarida, Gali, Gertler (1999) estimate $\rho_R = 0.68$, $\rho_\pi = 0.83$, $\rho_y = 0.0675$ for 1960Q1 to 1979Q2, and $\rho_R = 0.79$, $\rho_\pi = 2.15$, $\rho_y = 0.23$ for the 1979Q3 to 1996Q4 period. Orphanides (2003) re-examines the question with real-time data, and finds that the estimates values of Taylor rule coefficients are relatively more stable over the two periods: $\rho_R = 0.70$, $\rho_\pi = 1.64$, $\rho_y = 0.14$ in 1966Q1 to 1979Q2 and $\rho_R = 0.79$, $\rho_\pi = 1.80$, $\rho_y = 0.0675$ in 1979Q3 to 1995Q4. The difficulties with estimation of forward-looking Taylor rules are primarily due to the unobservable nature of both the output gap and expected inflation. In any case, calibrated values of all the parameters in the model, other than the capital adjustment cost parameter φ, are completely independent of the Taylor rule coefficients. Moreover, the value of φ is determined primarily by the standard deviation of the investment-to-consumption ratio and shows very little sensitivity to large variations in the Taylor rule coefficients.

It is readily apparent that the model tends to underpredict the degree of persistence found in the data. Overall, however, the fit of the model seems satisfactory as measures of volatility are replicated quite closely. Interestingly, a variance decomposition shows that 86 percent of volatility in hours in the model is due to risk premium shocks, suggesting that shocks emanating from financial markets have a powerful effect on the economy. This prediction of our model is quite similar, at least in spirt, to a number of recent papers. Nolan and Thoenissen (2009) work within a calibrated DSGE New Keynesian framework and find financial accelerator shocks to account for a large portion of the variance of output. Christiano, Motto and Rostagno (2007) augment a standard monetary DSGE model as developed by Christiano, Eichenbaum and Evans (2005) with financial markets to study, among other things, the role of financial shocks for business cycle fluctuations. The authors estimate their model on U.S. and Euro Area data and find financial market disturbances to be a key factor driving movements in important macroeconomic variables. Along the empirical margin, Gilchrist, Yankov and Zakrajsek (2009) carefully construct measures of credit market disruptions based on a broad range of credit spreads and estimate credit market shocks to be important for U.S. economic fluctuations.

4 Results

This section reports results generated from the non-linear model under a monetary policy of zero inflation. We focus on a zero ex-post inflation policy for three reasons. First, and perhaps most importantly, previous research within sticky price models has found zero inflation to be a good approximation to optimal monetary policy. Second, a zero inflation framework facilitates comparison with the results reported in Schmitt-Grohe and Uribe (2005) and Christiano (2004) who also consider the zero bound problem under a policy of zero inflation. Third, the non-linear model with non-zero inflation is extremely difficult to solve as varying inflation leads to a larger state space that includes price dispersion, in addition to capital and exogenous shocks.[19] For computation of the model, we use the projection with endogenous-grid-points method developed in Carroll (2006).[20] The method allows us to handle a relatively large state-space problem complicated by non-linearities owing to the zero-bound constraint.

[19]Moreover, consideration of Taylor rules with interest rate smoothing adds a lagged risk-free rate to the set of endogenous state variables.

[20]Details are in Appendix "C".

In contrast to the previous literature studying monetary policy in quantitative DSGE models, we find an important role for the zero bound on the nominal interest rate. Indeed, our quantitative model implies that the probability of approaching the effective zero bound (i.e. a risk-free rate less than 0.05 percent) is about 1.7 percent.[21] In other words, the zero bound should bind, on average, once every 15 years. Further exploration indicates that the relevance of the zero bound is owing to the presence of a risk premium shock. More specifically, we shut down the risk premium shocks by setting $\sigma_{\varepsilon_\tau} = 0$, while holding all other parameters at their benchmark values. We recompute the model assuming that the households know that the risk premium will be constant over time. We then evaluate the probability of reaching the zero bound under the zero-inflation policy.[22] In this case, the probability of observing of risk-free interest rate less than 0.05 percent is virtually zero. To give a better sense of this result, we calculate a statistic that takes the lowest observed risk-free rate in the 10,000 quarters of simulation and then divides it by its standard deviation. This statistic, calculated to be 6.6, provides an indication of the distance between the lowest risk-free rate and the zero bound, normalized by the standard deviation of the risk-free rate.[23]

These results beg the question: What makes risk premium different from the other shocks under consideration? Intuition for the "special" role of risk premium shocks can be gained from the observation that these shocks are similar to time-varying taxes on capital in the sense that they drive a wedge between the (ex-ante) marginal rates of return on capital and savings. The higher risk premium leads to a widening of the spread between the expected rate of return on capital and the risk-free rate. This implies that either the expected rate of return on capital must increase, the risk-free rate must fall, or both rates must move apart to accommodate the higher risk premium. For a wide range of plausible parameter configurations, much of the increase in the risk premium is accommodated by a fall in the risk-free rate (leading to a more volatile risk-free rate). This feature increases the probability that the zero bound may bind.

[21] In our model fiat money creates an endogenous bound on nominal interest rates. Because the marginal utility of money is always positive, the net return on risk-free bonds must always be strictly greater than zero to eliminate arbitrage opportunities. For this reason, we chose a positive cutoff value of 0.05 percent (annualized) for our effective lower bound. Henceforth, a nominal interest rate below 0.05 percent is said to be at its effective lower bound.

[22] Columns 2 and 3 of Table 5 show simulation results with and without risk-premium shocks, under a zero-inflation policy in the model with the benchmark parameter values.

[23] Alternatively, we could report a ratio of the average risk-free rate and the standard deviation of the risk-free rate (i.e. t-statistic). Given that the distribution of the risk-free rate is not symmetric, however, such a statistic may not be especially informative.

In contrast, the other aggregate shocks we examine do not move the rate of return on capital and the risk-free rate in opposite directions. Instead, both expected returns move in the same direction and by roughly the same proportion so the zero bound can only be reached with extreme realizations of these shocks.

Overall, the results from the experiment without the risk premium shocks are consistent with the findings reported in Schmitt-Grohe and Uribe (2005), which show that in a model with government spending, neutral productivity and investment-specific productivity shocks, optimal (near zero inflation) monetary policy is not constrained by the zero bound on nominal interest rates. In addition, the results with the risk premium shocks support Christiano's (2004) conjecture that other shocks might make the zero bound relevant for monetary policy design. Our results suggest that the presence of risk premium shocks may make a zero-inflation policy inconsistent with the objective of not hitting the zero bound on nominal interest rates.

5 Sensitivity analysis

In this section we examine the sensitivity of the model's properties as well as our key result regarding the relative importance of risk premium shocks for the zero bound on nominal interest rates. In particular, we report results from the following perturbations: (i) a reduction of the volatility of the risk premium shocks; (ii) an increase and decrease the average real return on risk-free government bonds; and (iii) a threefold increase in the magnitude of investment-specific technological shocks. We focus on these three cases since we find them to be the quantitatively most important from a wide range of other sensitivity experiments conducted.

We conduct the sensitivity analysis in two steps. First, for each experiment, we recalibrate the model using the same procedure as in the benchmark case to maintain the same relative volatilities of the simulated macroeconomic variables as in the data. We then use the recalibrated model to generate data to compare with the benchmark model. This step gives us an indication of the sensitivity of the model properties to different experiments. In the second step, we use the recalibrated model, constrain monetary policy to follow a zero inflation policy, and study the zero bound problem as in the previous section.

5.1 Risk premium shocks

The magnitude of the risk premium shocks is clearly important for our results. As such, we examine the sensitivity of our results to a more conservative measure of risk premium shocks. That is, we use Campello, Chen and Zhang's (2008) least volatile ex-ante equity premium series corresponding to the AAA- and AA-rated groups of U.S. corporations. These data produce a risk premium shock series that is slightly more persistent ($\rho_\tau = 0.88$), but substantially less volatile ($\sigma_{\varepsilon_\tau} = 0.0029$) than the benchmark BBB risk premium shocks. Table 3 reports the recalibration results. The first column provides a list of model parameters, the second column reproduces the benchmark calibration results, and the third column gives the recalibrated parameter values based on the less volatile risk premium shock series. We see a number of small changes across the parameters but only the capital adjustment parameter (φ) displays a notable movement, specifically: a fall from 18.6 to 7.8. This decline allows the model to match the volatility of investment despite a lower variance of the risk premium shock.

The benchmark and recalibrated model moments are reported in Table 4. The first column of the table lists the variables under consideration. The second and third columns reproduce the standard deviations and autocorrelations for the variables from the benchmark case. The following two columns report the same two moments for the less volatile risk premium experiment. Comparing the statistics listed in the four columns we see very little change across model moments, suggesting that the model is robust to changes in the volatility of the risk premium shock.

Table 5 reports simulation results for the (re-calibrated) model under the zero-inflation policy. The variables under consideration are given in column one. The second and third columns reproduce statistics from the benchmark case. The second column shows results with risk premium shocks while the third column displays corresponding results when the risk premium shocks are shut down (by setting $\sigma_{\varepsilon_\tau} = 0$). The following two columns report the same statistics for the lower volatility risk premium experiment. Looking across these rows, we see that the main message is unchanged: With the risk premium shocks there is a small but non-negligible probability of the risk-free rate being at the effective zero bound. In contrast, the version of the model without risk premium shocks is less volatile and the probability of approaching the zero bound is extremely low. More specifically, a four standard deviation (of the risk-free rate) band separates the lowest (simulated) risk-free rate and zero. Overall, even with relatively more conservatively-measured risk premium shocks, the main result is unchanged.

5.2 Real risk-free interest rate

The average real return on risk-free bonds determines the distance between the nominal risk-free rate and its zero bound, influencing the probability of approaching the bound. Moreover, the ex-ante real rate of return is not directly observable so there is some degree of uncertainty regarding its appropriate value. Given these two factors, we conduct a sensitivity analysis with two alternative rates of return, *viz.*, average rates of return of two and three percent annualized or $\overline{r} = 1.02^{0.25}$ and $\overline{r} = 1.03^{0.25}$, respectively. These two values cover a one percentage point range around our benchmark value of 2.5 percent.

Changes in the average real risk-free rate lead to a few changes in parameter calibrations. The fourth column of Table 3 contains the recalibrated parameter values under a lower real risk-free rate. While most of the parameters change only slightly, the capital adjustment parameter displays a relatively larger change, from 18.6 in the benchmark to 20.5 under this alternative scenario. A higher φ offsets an increase in investment volatility arising from the zero bound on the risk-free rate. When the average real risk-free rate is closer to zero, there is less room for the rate to adjust downward. When the spread between the rate of return on capital and the risk-free rate rises (because of an increase in the risk premium), more of the adjustment is borne by the capital return, and hence by investment. The following column of Table 3 shows the re-calibrated parameter values with a higher average risk-free rate relative to the benchmark case. Again, the model parameters remain virtually the same except for the value of the capital adjustment coefficient which is now slightly lower than in the benchmark. The higher average risk-free rate gives more scope for the risk-free rate to adjust downward and, therefore, less adjustment by the returns to physical capital and investment is required.

Columns 6 to 9 of Table 4 show simulated moments from the model with the calibrated Taylor rule under two assumption for the real risk-free rate ($\overline{r} = 1.02^{0.25}$ and $\overline{r} = 1.03^{0.25}$). Again there is very little change relative to the moments generated from the benchmark calibration.

Table 5 reports simulation results for zero-inflation policy. As we can see from column 6, a lower average risk-free rate coupled with risk premium shocks increases the probability of hitting the effective lower bound from 1.7 percent in the benchmark to 2.8 percent, or roughly once in 9 years. In the absence of risk premium shocks (column 7), the variables are much less volatile and there is a wide buffer zone between the range of the simulated risk-free rates and the effective zero bound. Columns 8 and 9 report the risk premium and no risk premium shock cases, respectively, under the assumption of a three percent average risk-free rate. These columns suggest that the qualitative results are similar under the two average risk-free rate cases. That is, although the probability of hitting the effective bound is lower, the conclusion regarding the relative importance of the risk premium shock stays intact.

Overall, we find that changing the value of the average risk-free interest rate does not affect the qualitative importance of risk premium shocks for hitting the effective zero bound on nominal interest rates.

5.3 Investment-specific shocks

The previous sections suggest that movements in investment may be a key component to our understanding of the zero bound problem in quantitative DSGE models. In this section, therefore, we consider the implications of an investment-specific productivity shock that is three times larger than its benchmark value (that is, $3 \cdot \sigma_{\varepsilon_x}$) for our main conclusion. The results are easily summarized. The last column of Table 3 presents the re-calibrated parameter values with the more volatile investment-specific shock series. Again, only the adjustment coefficient φ displays a meaningful change, from 18.6 to 19.9. The modestly higher value offsets an increase in the volatility of investment in an effort to match sample moments. The relative stability of the calibration results suggest the simulated moments from the recalibrated models should be quite similar to those from the benchmark model. This conjecture is confirmed by the statistics reported last two columns of Table 4. Finally, the last two columns of Table 5 report simulation results for zero-inflation policy with and without risk premium shocks. The quantitative results are similar to the benchmark and the qualitative results are unchanged. Overall, the results from this section indicate that the source of investment fluctuations is important for the zero bound issue. In particular, unlike risk premium perturbations, investment-specific productivity shocks (even inflated threefold from their empirically measured values) do not induce the risk-free rate to reach the zero bound.

5.4 Discussion of the sensitivity analysis

The sensitivity analysis results suggest that, once the model is recalibrated to match data moments, the qualitative results are quite robust to wide variations in the model parameters. Under the zero-inflation policy benchmark, risk premium shocks, even if conservatively measured, drive the risk-free rate to its effective zero bound. The other four shocks, even if grossly inflated, do not make zero-inflation policy inconsistent with the objective of staying away from the zero bound on the nominal interest rates.[24] The robustness of the main finding stems from the fact that the risk premium shocks, unlike the other shocks under consideration move the rates of return on capital and the risk-free rate in opposite directions. Owing to the fact that rapid changes in the rate of return on capital are costly, much of the adjustment to a widening spread is accommodated by the risk-free rate which in turn makes hitting the zero bound on nominal interest rates a higher probability event.

6 Price-Level Targeting

An alternative monetary policy framework that has received attention recently is price-level targeting. Eggertsson and Woodford (2003b) and Wolman (2005) show that price-level targeting rules are effective in reducing the probability of hitting the zero bound. As the authors explain, price-level targeting creates time-varying inflation expectations which move the real interest rate in a direction that helps to stabilize the economy. If a shock forces the current price level below the target, for example, private agents expect future inflation to be higher such that the price level returns to its target. This increase in expected inflation reduces the real interest rate, for any given level of the nominal interest rate, stimulates demand and leads to a rise in the price level to its target. As the price level approaches the target level, inflation expectations decrease, leading to a rise in the real interest rate and a reduction in stimulative effects of monetary policy. In other words, price-level targeting creates a stabilizing negative feedback effect from expected future inflation to the current real interest rate. We test the effectiveness of this stabilizing effect in our model by introducing a simple price-level targeting rule:

$$\log R_t = (1-\rho_R)\left(\log \bar{R} + \rho_p \log\left(\frac{P_t}{\bar{P}}\right) + \rho_y \log\left(\frac{y_t}{\bar{y}}\right)\right) + \rho_R \log R_{t-1}, \qquad (17)$$

where $\bar{P}$ is a constant price-level target. To give a sense of the possible results, we simply set the parameters of the price-level targeting rule to their counterpart values from the benchmark Taylor rule described in Section 3, including $\rho_p = \rho_\pi = 1.29$.

[24] These results are available from the authors upon request.

The second and third columns of Table 6 show the results from the cases with and without risk premium shocks, respectively. In the absence of risk premium shocks, we see that price-level targeting does as well as the zero-inflation policy (see, third column, Table 6 compared to column 3, Table 5). Looking across the cases of pricing-level targeting (second column of Table 6) and a zero-inflation policy (second column of Table 5) with risk premium shocks, we see that price-level targeting results in lower volatility of the risk-free rate and similar levels of variability in the other variables. Most interestingly, price-level targeting does, in this simple example, lead to a substantially lower (albeit still positive) probability of approaching the zero lower bound. Although the price-level targeting rule and its parameterization are quite arbitrary, the results suggest that price-level targeting may have potential for reducing the probability of reaching the zero bound on nominal interest rates. In future work, we plan on exploring optimal monetary policies in the face of risk premium shocks and the zero lower bound.

7 Concluding remarks

Recent real world events have demonstrated the importance of the zero bound on nominal interest rates as a consideration for monetary policy. Quantitative DSGE models, however, find that the zero bound is not a pressing constraint for monetary policy when the central bank follows an optimal policy of stabilizing the price level. In this paper, we attempt to resolve this apparent disconnect by studying a quantitative DSGE model with a broader range of shocks than examined in earlier work. We find that under a zero inflation policy, risk premium shocks are the only shocks in our study that are capable of driving the risk-free rate to zero. The risk premium mechanism operates by increasing the spread between rates of return on private capital and the risk-free rate. Other common shocks, such as aggregate productivity, investment specific productivity, government spending and money demand shocks, are unable to push the risk-free rate close to zero since these shocks shift the risk-free rate and the expected return on capital in the same direction and roughly in the same proportions. These shocks, therefore, have weak implications for the zero bound problem and could only force nominal rates to zero following extreme realizations.

In sum, our results suggest that careful consideration of risk premium shocks may improve our understanding of the zero bound on nominal interest rate problem within a quantitative DSGE framework. There are at least three avenues for future research.

First, endogenizing the risk premium may lead to future insights on the zero bound problem, in particular, and optimal monetary policy, in general. Second, it would be useful to derive optimal monetary policy in a DSGE model where the zero bound is important. Third, our results suggest that price-level targeting warrants additional research in quantitative models with risk premium shocks when the monetary authority is concerned with hitting the zero lower bound.

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A Data sources and data transformations

Monthly risk premium series were downloaded from Lu Zhang's website in September 2008. The data are converted into quarterly frequency by taking the average over three months of each quarter (or over two months in two quarters with missing BBB data points). Since the risk premium are reported on an annualized basis, we also divide the values by four.

Nominal labour income share as well as the other five nominal ratios: (i) gross investment-to-GDP; (ii) private consumption-to-GDP; (iii) government consumption-to-GDP; (iv) gross investment-to-private consumption; and (v) monetary base-to-private consumption; were computed from nominal, seasonally-adjusted, quarterly-frequency US NIPA data (taken from IFS-IMF dataset). The nominal investment series includes government investment and net exports. The monetary base series comes from BIS. The nominal labour income share is computed by dividing the "Compensation of employees received" series by the nominal GDP.

Seasonally-adjusted, quarterly-frequency real US GDP and real US capital stock series are taken from OECD Economic Outlook datasets. The aggregate hours worked index (total economy) is taken from Francis and Ramey's (2005) dataset downloaded from Valerie Ramey‘s website (June 10, 2008 version). The TFP series are constructed from the real GDP (Y), real capital (K) and aggregate hours worked (H) series as follows: $\ln A = \ln Y - \alpha \ln H - (1 - \alpha) \ln K$.

The annual-frequency US working-age population data also come from OECD Economic Outlook. These population data are converted to quarterly frequency by simple linear interpolation.

The aggregate working hours-per-working age person *index* is taken from Francis and Ramey (2005) dataset. We normalize this index to have its mean equal to 0.25, which is the average 1974Q1-1998Q1 fraction of the working hours in the dataset compiled by Cociuba, Prescott and Ueberfeldt (2009).

The risk-free rate series is proxied by the "3-Month Treasury Bill Rate: Auction Average" series available from the FRED database (TB3MA). We take the average of monthly rates in each quarter. We then divide the numbers by four to convert them from the annualized rates to quarterly rates.

Finally, the PCE inflation rate is computed from the BEA PCE (seasonally adjusted, quarterly-frequency) price index.

All the series, except the government consumption-to-GDP data, are taken over the sample period of 1974Q1-1998Q1, to be consistent with the ex-ante equity risk premium constructed by Campello, Chen and Zhang (2008). As was noted above, the nominal government consumption-to-GDP ratio are taken over a longer time period, 1974Q1-2008Q2, to avoid cutting the series off at the bottom of a 1991-1999 downward trend, which is largely reversed thereafter.

B Detrending the model

There are two non-stationary processes for technology in the model, A_t and X_t. As shown in Fisher (2006) we can detrend consumption, output and other variables as follows:

$$y_t = \frac{Y_t}{\Omega_t}, \quad c_t = \frac{Y_t}{\Omega_t}, \quad m_t = \frac{M_t}{P_t \Omega_t}, \quad \lambda_t = \Lambda_t \Omega_t, \quad k_t = \frac{K_t}{\Omega_t X_t},$$

where

$$\Omega_t = A_t^{\frac{1}{\alpha}} X_t^{\frac{1-\alpha}{\alpha}}.$$

This implies that (non-detrended) consumption, output and real money balances grow at a long-run average rate, $\gamma_y = \exp\left(\frac{g_a+(1-\alpha)g_x}{\alpha}\right)$, while the capital stock grows at a long-run average rate, $\gamma_k = \exp\left(\frac{g_a+g_x}{\alpha}\right)$.

Defining $p_t^* = \frac{P_t^*}{P_t}$, restating all the household's first-order conditions and market-clearing conditions with detrended variables, and simplifying, we obtain the following system of equations:

$$\frac{c_t^{-\frac{1}{\gamma}}}{c_t^{\frac{\gamma-1}{\gamma}} + u_t^{\frac{1}{\gamma}} m_t^{\frac{\gamma-1}{\gamma}}} = \lambda_t$$

$$\left(\frac{u_t c_t}{m_t}\right)^{\frac{1}{\gamma}} = 1 - \frac{1}{R_t}$$

$$\frac{\eta}{1-h_t} = \lambda_t w_t$$

$$\frac{\lambda_t}{R_t} = \beta E_t \left(\frac{\lambda_{t+1}}{\pi_{t+1}} \frac{\Omega_t}{\Omega_{t+1}}\right)$$

$$\lambda_t k_t \left[1 + \varphi\left(\frac{k_t}{\chi_t} - \gamma_k\right)\right] = \beta E_t \left\{\lambda_{t+1}\chi_{t+1}\left[1 - \delta + q_{t+1} - \tau_t + \frac{\varphi}{2}\left(\left(\frac{k_{t+1}}{\chi_{t+1}}\right)^2 - \gamma_k^2\right)\right]\right\}$$

$$1 = (1-d)\left(p_t^*\right)^{1-\theta} + d\pi_t^{\theta-1}$$

$$\Phi_t = \lambda_t \psi_t y_t + \beta d E_t \left[\pi_{t+1}^{\theta} \Phi_{t+1}\right]$$

$$\Gamma_t = \lambda_t y_t + \beta d E_t \left[\pi_{t+1}^{\theta-1} \Gamma_{t+1}\right]$$

$$p_t^* = \frac{\theta}{\theta-1} \frac{\Phi_t}{\Gamma_t}$$

$$q_t = (1-\alpha)\psi_t \left[\frac{\chi_t}{h_t}\right]^{-\alpha}$$

$$w_t = \alpha\psi_t \left[\frac{\chi_t}{h_t}\right]^{1-\alpha}$$

$$c_t + k_t - \left[1 - \delta - \frac{\varphi}{2}\left(\frac{k_t}{\chi_t} - \exp\left(\frac{g_a + g_x}{\alpha}\right)\right)^2\right]\chi_t = y_t(1 - g_t)$$

$$\chi_t^{1-\alpha} {h_t}^{\alpha} = y_t S_t$$

$$S_t = (1-d)p_t^{*-\theta} + d{\pi_t}^{\theta} S_{t-1},$$

$$\chi_t = k_{t-1}\frac{\Omega_{t-1}X_{t-1}}{\Omega_t X_t}$$

plus a monetary policy equation

$$\pi_t = 1$$

under the zero-inflation policy, or

$$\log R_t = (1-\rho_R)\left(\log \bar{R} + \rho_\pi E_t\left[\log\left(\frac{\pi_{t+1}}{\bar{\pi}}\right)\right] + \rho_y \log\left(\frac{y_t}{\bar{y}}\right)\right) + \rho_R \log R_{t-1} + \varepsilon_{R,t}, \quad (18)$$

with a forward looking Taylor rule. In the Taylor rule $\bar{y}$ is simply the steady-state value of detrended output, y_t.

C Computation

For computational purposes, we use a combination of a parameterized-expectations approach with the endogenous grid method described in Carroll (2006) for non-linear computations of the model with zero-inflation policy. To be specific:

1. Take Chebyshev grids over $(\ln k_t, \tau_t, g_t, \ln u_t)$, and over $(\ln \chi_t, \tau_t, g_t, \ln u_t)$, where $\chi_t = k_{t-1}\frac{\Omega_{t-1}X_{t-1}}{\Omega_t X_t}$.

2. Guess the expectation functions:

$$f_1^{(0)}(\ln k_t, \tau_t, g_t, \ln u_t) \equiv E_t\left(\beta\lambda_{t+1}\frac{\Omega_t}{\Omega_{t+1}}\right)$$

and

$$f_2^{(0)}(\ln k_t, \tau_t, g_t, \ln u_t) \equiv E_t\left\{\lambda_{t+1}\chi_{t+1}\left[1-\delta+q_{t+1}-\tau_t+\frac{\varphi}{2}\left(\left(\frac{k_{t+1}}{\chi_{t+1}}\right)^2-\gamma_k^2\right)\right]\right\}.$$

3. For each combination of the state variables $(\ln k_t, \tau_t, g_t, \ln u_t)$ from the grid, solve for χ_t, R_t, w_t, q_t, and $\widetilde{c}_t \equiv \frac{c_t}{\chi_t}$, $\widetilde{m}_t \equiv \frac{m_t}{\chi_t}$, $\widetilde{h}_t \equiv \frac{h_t}{\chi_t}$, $\widetilde{y}_t \equiv \frac{y_t}{\chi_t}$ $\widetilde{\lambda}_t \equiv \lambda_t\chi_t$ and the following set of equations

$$\frac{\widetilde{c}_t^{-\frac{1}{\gamma}}}{\widetilde{c}_t^{\frac{\gamma-1}{\gamma}}+u_t^{\frac{1}{\gamma}}\widetilde{m}_t^{\frac{\gamma-1}{\gamma}}}=\widetilde{\lambda}_t$$

$$\left(\frac{u_t\widetilde{c}_t}{\widetilde{m}_t}\right)^{\frac{1}{\gamma}}=1-\frac{1}{R_t}$$

$$\frac{\eta}{\frac{1}{\chi_t}-\widetilde{h}_t}=\widetilde{\lambda}_t w_t,$$

$$\frac{\widetilde{\lambda}_t}{R_t\chi_t}=f_1^{(i)}(\ln k_t, \tau_t, g_t, \ln u_t)$$

$$\widetilde{\lambda}_t\frac{k_t}{\chi_t}\left[1+\varphi\left(\frac{k_t}{\chi_t}-\gamma_k\right)\right]=f_2^{(i)}(\ln k_t, \tau_t, g_t, \ln u_t)$$

$$q_t=(1-\alpha)\frac{\theta-1}{\theta}\left[\widetilde{h}_t\right]^{\alpha}$$

$$w_t=\alpha\frac{\theta-1}{\theta}\left[\widetilde{h}_t\right]^{\alpha-1}$$

$$\widetilde{c}_t + \frac{k_t}{\chi_t} - \left[1 - \delta - \frac{\varphi}{2}\left(\frac{k_t}{\chi_t} - \gamma_k\right)^2\right] = \widetilde{y}_t(1 - g_t)$$

$$\widetilde{h}_t^{\alpha} = \widetilde{y}_t$$

in which we take account of the fact that $\psi_t = \frac{\theta-1}{\theta}$, $S_t = 1$, and $p_t^* = 1$ under the zero-inflation policy, $\pi_t - 1 = 0$.

4. With the above variables computed, use projection methods to approximate the following functions

$$g_1^{(i)}(\ln \chi_t, \tau_t, g_t, \ln u_t) \equiv \beta \widetilde{\lambda}_t$$

$$g_2^{(i)}(\ln \chi_t, \tau_t, g_t, \ln u_t) \equiv 1 - \delta + q_t + \frac{\varphi}{2}\left(\left(\frac{k_t}{\chi_t}\right)^2 - \gamma_k^2\right)$$

5. For each pair $(\ln k_t, \tau_t, g_t, \ln u_t)$ from the same grid as in step 1, use the Gauss-Legendre quadrature values of $(\varepsilon_a, \varepsilon_x, \varepsilon_\tau, \varepsilon_g, \varepsilon_u)$ together with their associated probabilities, and with the laws of motion

$$\ln \chi_{t+1} = \ln k_t - \frac{g_a + g_x}{\alpha} - \frac{\varepsilon_{a,t+1} + \varepsilon_{x,t+1}}{\alpha}$$

$$\tau_{t+1} = (1 - \rho_\tau)\,\bar{\tau} + \rho_\tau \tau_t + \varepsilon_{\tau,t+1}$$

$$g_{t+1} = \left(1 - \rho_g\right)\bar{g} + \rho_g g_t + \varepsilon_{g,t+1}$$

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

to compute the expectations

$$E_t\left(\beta \frac{\widetilde{\lambda}_{t+1}}{\chi_{t+1}} \frac{\Omega_t}{\Omega_{t+1}}\right) = E_t\left(\frac{g_1^{(i)}(\ln \chi_{t+1}, \tau_{t+1}, g_{t+1}, \ln u_{t+1})}{\chi_{t+1}} \frac{\Omega_t}{\Omega_{t+1}}\right)$$

$$\begin{aligned} & E_t\left\{\beta \widetilde{\lambda}_{t+1}\left[1 - \delta + q_{t+1} - \tau_t + \frac{\varphi}{2}\left(\left(\frac{k_{t+1}}{\chi_{t+1}}\right)^2 - \gamma_k^2\right)\right]\right\} \\ = \; & E_t\left[g_1^{(i)}(\ln \chi_{t+1}, \tau_{t+1}, g_{t+1}, \ln u_{t+1})\left\{g_2^{(i)}(\ln \chi_{t+1}, \tau_{t+1}, g_{t+1}, \ln u_{t+1}) - \tau_t\right\}\right]. \end{aligned}$$

6. Use the expectations computed above to update the approximated functions

$$f_1^{(i+1)}(\ln k_t, \tau_t, g_t, \ln u_t) \equiv E_t \left(\beta \frac{\widetilde{\lambda}_{t+1}}{\chi_{t+1}} \frac{\Omega_t}{\Omega_{t+1}} \right)$$

$$f_2^{(i+1)}(\ln k_t, \tau_t, g_t, \ln u_t) \equiv E_t \left\{ \beta \widetilde{\lambda}_{t+1} \left[1 - \delta + q_{t+1} - \tau_t + \frac{\varphi}{2} \left(\left(\frac{k_{t+1}}{\chi_{t+1}} \right)^2 - \gamma_k^2 \right) \right] \right\}$$

by fitting polynomial functions defined on the space of $(\ln k, \tau, g, \ln u)$.

7. Iterate on steps 3-6 until convergence of the expectations functions $f_1^{(i)}$, $f_2^{(i)}$.

Table 1: Benchmark parameter values

Parameter	Description	Value
β	Discount factor	0.998
γ	Elasticity of substitution between C_t and M_t/P_t	0.06
η	Utility weight on leisure	2.7
φ	Coefficient of capital adjustment	18.6
δ	Capital depreciation rate	0.026
θ	Elasticity of substitution for intermediate goods	7.7
α	Coefficient on h_t in Cobb-Douglas production function	0.67
d	Calvo probability of unchanged price next period	0.67
	Taylor rule coefficients	
ρ_R	Interest rate smoothing	0.51
ρ_π	Expected inflation	1.29
ρ_y	Detrended output	0.034
$\bar{\pi}^4 - 1$	Target inflation rate (annualized), percentage	3.6
	Unconditional expectation of the shock terms	
g_a	Drift term for neutral productivity shock	0.0019
g_x	Drift term for investment-specific productivity shock	0.0029
$\bar{g}$	Average government consumption share in output	0.162
$\bar{u}$	Average value of money demand shock	0.062
$\bar{\tau}$	Average risk premium	0.016
	First-order autocorrelation coefficient for shocks	
ρ_τ	Risk premium	0.84
ρ_u	Money demand	0.97
ρ_g	Government consumption share	0.98
	Standard deviations of shocks	
$\sigma_{\varepsilon_\tau}$	Risk premium	0.0079
σ_{ε_u}	Money demand	0.01
σ_{ε_g}	Government consumption share	0.002
σ_{ε_x}	Investment-specific productivity	0.0055
σ_{ε_a}	Neutral productivity shock	0.0062

Table 2: Calibration Results

Variable	Data		Benchmark Model	
	st. dev.	ar(1)	st.dev.	ar(1)
Hours	0.80	0.99	0.80	0.78
Inflation	0.68	0.86	0.68	0.79
Investment/GDP	1.60	0.93	1.64	0.82
Investment/Consumption	**3.26**	0.93	**3.26**	0.82
Labour income share	**0.92**	0.87	**0.92**	0.65
Risk-free rate	**0.63**	**0.95**	**0.63**	**0.95**

Note: The terms "st. dev." and "ar(1)" refer to standard deviation and first-order autocorrelation coefficient, respectively. The numbers in bold font are the calibration target moments. Standard deviations are in percentage points.

Table 3: Sensitivity analysis: calibrated parameter values

Parameter	Benchmark value	AAA/AA shock	$R_t = 2\%$	$R_t = 3\%$	σ_x= 1.65%
1	2	3	4	5	6
β	0.998		0.999	0.997	
η	2.7		2.7	2.7	
δ	0.026		0.024	0.028	
θ	7.7		7.7	7.7	
φ	18.6	7.8	20.5	17.0	19.9
ρ_R	0.51	0.51	0.51	0.51	0.53
ρ_π	1.29	1.27	1.27	1.30	1.38
ρ_y	0.034	0.028	0.031	0.038	0.001

Note: Empty cells indicate parameters that are unaffected by the recalibration exercise.

Table 4: Sensitivity analysis: simulated moments with calibrated Taylor rules

Standard deviation of	Benchmark		AAA/AA		$R_t = 2\%$		$R_t = 3\%$		σ_x= 1.65%	
	st.dev	ar(1)	st.dev	ar(1)	st.dev	ar(1)	st.dev	ar(1)	st.dev	ar(1)
	2	3	4	5	6	7	8	9	10	11
Hours	0.80	0.78	0.80	0.77	0.80	0.78	0.81	0.78	0.80	0.78
Inflation	0.68	0.79	0.68	0.78	0.69	0.79	0.67	0.79	0.67	0.76
Investment/GDP	1.64	0.82	1.64	0.82	1.64	0.82	1.64	0.82	1.64	0.83
Investment/Consumption	3.26	0.82	3.26	0.82	3.26	0.82	3.26	0.82	3.26	0.84
Labour income share	0.92	0.65	0.92	0.61	0.92	0.65	0.92	0.65	0.92	0.63
Risk-free rate	0.63	0.95	0.63	0.95	0.63	0.95	0.63	0.95	0.63	0.95

Note: The terms "st. dev." and "ar(1)" refer to standard deviation and first-order autocorrelation coefficient, respectively.

Table 5: Sensitivity analysis: simulation results with and without risk-premium shocks under zero-inflation policy

Standard deviation of	Benchmark		AAA/AA		$R_t = 2\%$		$R_t = 3\%$		σ_x= 1.65%	
	RP	no RP	RP	no RP	RP	no RP	RP	no RP	RP	no RP
	2	3	4	5	6	7	8	9	10	11
Hours	0.54	0.29	0.50	0.31	0.55	0.29	0.53	0.29	0.53	0.31
Investment/GDP	1.58	0.29	1.45	0.50	1.59	0.30	1.58	0.27	1.58	0.53
Consumption/GDP	1.85	0.99	1.73	1.09	1.85	0.99	1.84	1.00	1.82	1.08
Detrended GDP	1.55	0.97	0.97	0.79	1.62	1.02	1.51	0.92	2.15	1.77
Risk-free rate	0.31	0.06	0.26	0.08	0.30	0.06	0.32	0.06	0.32	0.12
p-value of $R_t < 5bps$	1.70	0	0.58	0	2.76	0	0.48	0	1.75	0
min(R_t) /st. dev. (R_t)	-	6.6	-	4.1	-	4.9	-	8.1	-	2.1

Note: The term "RP" indicates the model with the risk premium shock and "no RP" to the model without the risk premium shock. The last row shows the minimum risk-free rate divided by the standard deviation of the risk-free rate.

Table 6: Simulation results for Price level targeting

Standard deviation of	with RP shocks	no RP shocks
Hours	0.56	0.26
Investment/GDP	1.54	0.29
Consumption/GDP	1.78	0.89
Detrended GDP	1.56	0.96
Risk-free rate	0.21	0.06
p-value of $R_t < 5bps$	0.12	0
min(R_t) /st. dev. (R_t)	-	7.4

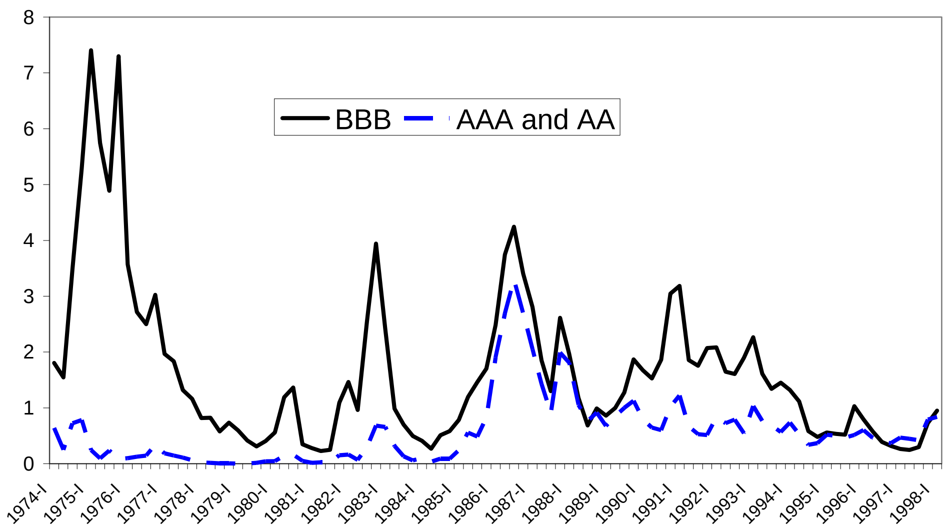

Figure 1: Ex-ante equity risk premium for BBB and AAA/AA US corporations. Source: Camplello, Chen and Zhang (2008). The original series were converted to the quarterly basis.