Is Rotemberg Pricing Justified by Macro Data?*

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Abstract

Structural models used to study monetary policy often include sticky prices. Calvo pricing is more common but Rotemberg pricing has become popular due to its computational advantage. To determine whether the data supports that change, we estimate a nonlinear New Keynesian model with a zero lower bound (ZLB) constraint and each type of sticky prices. The models produce similar parameter estimates and the filtered shocks are nearly identical when the Fed was not constrained, but the Rotemberg model has a higher marginal data density and it endogenously generates more volatility at the ZLB, which helps explain data from 2008-2011.

Keywords: Bayesian Estimation; Calvo Pricing; Rotemberg Pricing; Zero Lower Bound
JEL Classifications: C11; E43; E58

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1 INTRODUCTION

Structural models used to study monetary policy often include sticky prices. The most common ways to introduce sticky prices are with Rotemberg (1982) price adjustment costs and Calvo (1983) random price changes. With Rotemberg pricing firms choose identical prices because they face the same cost, whereas with Calvo pricing firms differ based on when their price was last reset. Therefore, the Calvo model contains one additional state variable that tracks firm price dispersion.

Historically linear models provided a good approximation of the data, but the 2008 recession caused many central banks to reduce their policy rate to its zero lower bound (ZLB). The ZLB created a kink in the monetary policy rule, which required nonlinear solution and estimation techniques to accurately assess its empirical implications. Unlike linear models, the solution time in nonlinear models increases with the number of state variables. As nonlinear methods became more important, Rotemberg pricing increased in popularity.[1] To determine whether US data supports that change, we estimate a nonlinear New Keynesian model with a ZLB and each type of sticky prices.

The two pricing mechanisms produce the same dynamics with a first-order approximation of the model when trend inflation is zero or there is full indexation to inflation, but differences occur when those conditions do not hold or the solution is based on a higher-order approximation.[2] We assume full indexation to trend inflation to focus on the role of the ZLB and higher order moments. The two models produce similar parameter estimates and the filtered shocks are nearly identical when the Fed was not constrained, but the Rotemberg model has a higher marginal data density and it endogenously generates more volatility at the ZLB, which helps explain data from 2008-2011.[3]

The paper proceeds as follows. Section 2 lays out the model with Rotemberg and Calvo pricing, including the solution and estimation procedures. Section 3 compares the parameter estimates, data densities, impulse responses, shocks, and frequency/duration of ZLB events. Section 4 concludes.

2 STRUCTURAL MODELS

2.1 HOUSEHOLDS A representative household chooses $\{c_t, n_t, b_t\}_{t=0}^{\infty}$ to maximize expected lifetime utility, $E_0 \sum_{t=0}^{\infty} \tilde{\beta}_t[\log(c_t - hc^a_{t-1}) - \chi n_t^{1+\eta}/(1+\eta)]$, where $\chi > 0$, $1/\eta$ is the Frisch elasticity of labor supply, c is consumption, c^a is aggregate consumption, h is the degree of external habit persistence, n is labor hours, b is the real value of a privately-issued 1-period nominal bond, E_0 is an expectation operator conditional on information in period 0, $\tilde{\beta}_0 \equiv 1$, and $\tilde{\beta}_t = \prod_{j=1}^{t>0} \beta_j$. To introduce fluctuations in the real interest rate, the discount factor, β, is time-varying and follows

$$\log \beta_t = (1-\rho_\beta)\log\bar{\beta} + \rho_\beta \log\beta_{t-1} + \sigma_\upsilon \upsilon_t,\ 0 \le \rho_\beta < 1,\ \upsilon \sim \mathbb{N}(0,1), \tag{1}$$

where $\bar{\beta}$ is the discount factor along the steady state growth path. The choices are constrained by $c_t + b_t = w_t n_t + i_{t-1}b_{t-1}/\pi_t + d_t$, where π is the gross inflation rate, w is the real wage rate, i is the gross nominal interest rate, and d is a real dividend. The household's optimality conditions imply

$$w_t = \chi n_t^\eta (c_t - hc^a_{t-1}),$$
$$1 = i_t E_t[q_{t,t+1}/\pi_{t+1}],$$

where $q_{t,t+1} \equiv \beta_{t+1}(c_t - hc^a_{t-1})/(c_{t+1} - hc^a_t)$ is the pricing kernel between periods t and $t+1$.

[1] This is especially true for nonlinear estimation (Aruoba et al. (2016); Gust et al. (2016); Plante et al. (2016)). Papers that use Calvo pricing include Fernández-Villaverde et al. (2015), Maliar and Maliar (2015), and Nakata (2015).

[2] See, for example, Ascari et al. (2011), Ascari and Rossi (2012), Lombardo and Vestin (2008), and Nisticò (2007).

[3] Miao and Ngo (2014) compare the two pricing mechanisms in a calibrated nonlinear model with a ZLB constraint.

2.2 FIRMS The production sector consists of a continuum of monopolistically competitive intermediate goods firms owned by households and a final goods firm. Intermediate firm $f \in [0,1]$ produces a differentiated good, $y_t(f)$, according to $y_t(f) = z_t n_t(f)$, where $n(f)$ is the labor hired by firm f and $z_t = g_t z_{t-1}$ is technology. The deviations from the steady state growth rate, $\bar{g}$, follow

$$\log g_t = (1-\rho_g)\log \bar{g} + \rho_g \log g_{t-1} + \sigma_\varepsilon \varepsilon_t,\ 0 \leq \rho_g < 1,\ \varepsilon \sim \mathbb{N}(0,1). \tag{2}$$

Each intermediate firm chooses its labor to minimize its costs, $w_t n_t(f)$, subject to its production function. The final goods firm purchases $y_t(f)$ units from each intermediate firm to produce the final good, $y_t \equiv [\int_0^1 y_t(f)^{(\theta-1)/\theta} df]^{\theta/(\theta-1)}$, where $\theta > 1$ measures the elasticity of substitution between intermediate goods. It then maximizes dividends to determine its demand function for intermediate good f, $y_t(f) = (p_t(f)/p_t)^{-\theta} y_t$, where $p_t = [\int_0^1 p_t(f)^{1-\theta} df]^{1/(1-\theta)}$ is the price level.

2.2.1 MODEL 1: PRICE ADJUSTMENT COSTS Following Rotemberg (1982), each intermediate firm faces a cost to adjusting its price, $adj_t(f) = \varphi[p_t(f)/(\bar{\pi} p_{t-1}(f)) - 1]^2 y_t/2$, where $\varphi > 0$ scales the size of the cost and $\bar{\pi}$ is the gross inflation rate along the steady state growth path. Firm f chooses its price, $p_t(f)$, to maximize the expected discounted present value of future dividends, $E_t \sum_{k=t}^{\infty} q_{t,k} d_k(f)$, where $q_{t,t} \equiv 1$, $q_{t,k} \equiv \prod_{j=t+1}^{k>t} q_{j-1,j}$, and $d_t(f) = (p_t(f)/p_t) y_t(f) - w_t n_t(f) - adj_t(f)$. In symmetric equilibrium, firms choose the same price, so the optimality condition implies

$$\varphi(\hat{\pi}_t - 1)\hat{\pi}_t = 1 - \theta + \theta(w_t/z_t) + \varphi E_t[q_{t,t+1}(\hat{\pi}_{t+1} - 1)\hat{\pi}_{t+1}(y_{t+1}/y_t)],$$

where $\hat{\pi}_t \equiv \pi_t/\bar{\pi}$. When $\varphi = 0$, $w_t/z_t = (\theta-1)/\theta$, which is the inverse of the gross price markup.

2.2.2 MODEL 2: STAGGERED PRICES Following Calvo (1983), a fraction, ω, of intermediate firms cannot choose their price in a given period. Those firms index their price to steady-state inflation, so $p_t(f) = \bar{\pi} p_{t-1}(f)$. A firm that can set its price at t chooses p_t^* to maximize the expected discounted present value of future dividends, $E_t \sum_{k=t}^{\infty} \omega^{k-t} q_{t,k} d_k^*$, where $d_k^* = [(\bar{\pi}^{k-t} p_t^*/p_k)^{1-\theta} - (w_k/z_k)(\bar{\pi}^{k-t} p_t^*/p_k)^{-\theta}] y_k$. The optimality condition is given by $p_t^*/p_t = \theta x_{1,t}/((\theta-1)x_{2,t})$, where

$$x_{1,t} = (c_t - hc_{t-1})^{-1} y_t w_t/z_t + \omega E_t[\beta_{t+1}\hat{\pi}_{t+1}^{\theta} x_{1,t+1}],$$
$$x_{2,t} = (c_t - hc_{t-1})^{-1} y_t + \omega E_t[\beta_{t+1}\hat{\pi}_{t+1}^{\theta-1} x_{2,t+1}].$$

The aggregate price index and the level of price dispersion, $\Delta_t \equiv \int_0^1 (p_t(f)/p_t)^{-\theta} df$, are given by

$$\omega(\pi_t/\bar{\pi})^{\theta-1} = 1 - (1-\omega)(\mu x_{1,t}/x_{2,t})^{1-\theta},$$
$$\Delta_t = (1-\omega)(\mu x_{1,t}/x_{2,t})^{-\theta} + \omega \hat{\pi}_t^{\theta} \Delta_{t-1},$$

where $\mu = \theta/(\theta-1)$. Therefore, aggregate output is given by $y_t = z_t n_t/\Delta_t$, where $n_t \equiv \int_0^1 n_t(f)$.

2.3 MONETARY POLICY The central bank sets the gross nominal interest rate according to

$$i_t = \max\{\underline{\imath}, i_t^*\},\ i_t^* = (i_{t-1}^*)^{\rho_i}(\bar{\imath}\hat{\pi}_t^{\phi_\pi}(c_t/(\bar{g}c_{t-1}))^{\phi_c})^{1-\rho_i}\exp(\sigma_\nu \nu_t),\ 0 \leq \rho_i < 1,\ \nu \sim \mathbb{N}(0,1),$$

where $\underline{\imath}$ is the lower bound, i^* is the notional rate, ϕ_π and ϕ_c are the responses to deviations of inflation from target and deviations of consumption growth from its steady state, and $\bar{\imath}$ and $\bar{\pi}$ are the inflation and interest rate targets, which equal their values along the steady state growth path.

2.4 EQUILIBRIUM Given the unit root in technology, the model does not have a steady state. To make the model stationary, we redefine variables that grow in terms of technology (i.e., $\tilde{x}_t \equiv x_t/z_t$). In both models, the equilibrium system includes the stochastic processes, the ZLB constraint, the bond market clearing condition, $b_t = 0$, the aggregation rule, $\tilde{c}_t = \tilde{c}_t^a$, and the following equations:

$$\tilde{\lambda}_t = \tilde{c}_t - h\tilde{c}_{t-1}/g_t, \tag{3}$$

$$\tilde{w}_t = \chi n_t^\eta \tilde{\lambda}_t, \tag{4}$$

$$1 = i_t E_t[\beta_{t+1}(\tilde{\lambda}_t/\tilde{\lambda}_{t+1})(1/(g_{t+1}\bar{\pi}\hat{\pi}_{t+1}))], \tag{5}$$

$$i_t^* = (i_{t-1}^*)^{\rho_i}(\bar{\imath}\hat{\pi}_t^{\phi_\pi}(g_t\tilde{c}_t/(\bar{g}\tilde{c}_{t-1})^{\phi_c})^{1-\rho_i}\exp(\sigma_\nu\nu_t). \tag{6}$$

In addition to the above system of equations, Model 1 includes

$$\tilde{y}_t = n_t, \tag{7R}$$

$$\tilde{c}_t = [1 - \varphi(\hat{\pi}_t - 1)^2/2]\tilde{y}_t, \tag{8R}$$

$$\varphi(\hat{\pi}_t - 1)\hat{\pi}_t = (1-\theta) + \theta\tilde{w}_t + \varphi E_t[\tilde{\beta}_{t+1}(\tilde{\lambda}_t/\tilde{\lambda}_{t+1})(\hat{\pi}_{t+1} - 1)\hat{\pi}_{t+1}(\tilde{y}_{t+1}/\tilde{y}_t)], \tag{9R}$$

whereas Model 2 includes

$$\Delta_t\tilde{y}_t = n_t, \tag{7C}$$

$$\tilde{c}_t = \tilde{y}_t. \tag{8C}$$

$$x_{1,t} = \tilde{\lambda}_t^{-1}\tilde{y}_t\tilde{w}_t + \omega E_t\left\{\beta_{t+1}\hat{\pi}_{t+1}^\theta x_{1,t+1}\right\}, \tag{9C}$$

$$x_{2,t} = \tilde{\lambda}_t^{-1}\tilde{y}_t + \omega E_t\left\{\beta_{t+1}\hat{\pi}_{t+1}^{\theta-1} x_{2,t+1}\right\}, \tag{10C}$$

$$\omega\hat{\pi}_t^{\theta-1} = 1 - (1-\omega)(\mu x_{1,t}/x_{2,t})^{1-\theta}, \tag{11C}$$

$$\Delta_t = (1-\omega)(\mu x_{1,t}/x_{2,t})^{-\theta} + \omega\hat{\pi}_t^\theta\Delta_{t-1}. \tag{12C}$$

In Model 1, a competitive equilibrium consists of sequences of quantities, $\{\tilde{\lambda}_t, \tilde{c}_t, n_t, \tilde{y}_t\}_{t=0}^\infty$, prices, $\{w_t, i_t, i_t^*, \hat{\pi}_t\}_{t=0}^\infty$, and exogenous variables, $\{\beta_t, g_t\}_{t=0}^\infty$, that satisfy the detrended equilibrium system, given the initial conditions, $\{\tilde{c}_{-1}, i_{-1}^*, \beta_0, g_0, \nu_0\}$, and shocks, $\{\varepsilon_t, \upsilon_t, \nu_t\}_{t=1}^\infty$. The competitive equilibrium in Model 2 is the same as Model 1, except it has three new variables, $\{\Delta_t, x_{1,t}, x_{2,t}\}_{t=0}^\infty$.

Steady-State Discount Factor	$\bar{\beta}$	0.9984	Real GDP Growth Rate Measurement Error SD	$\sigma_{me,\hat{y}}$	0.00190
Frisch Elasticity of Labor Supply	$1/\eta$	3	Inflation Rate Measurement Error SD	$\sigma_{me,\pi}$	0.00077
Elasticity of Substitution between Goods	θ	6	Federal Funds Rate Measurement Error SD	$\sigma_{me,i}$	0.00210
Steady-State Labor	$\bar{n}$	0.33	Number of Particles	N_p	40,000
Nominal Interest Rate Lower Bound	$\underline{\imath}$	1.00017	Number of Posterior Draws	N_d	100,000

Table 1: Model and estimation parameters

2.5 SOLUTION METHOD AND ESTIMATION PROCEDURE We solve both models using policy function iteration. Each iteration, we minimize the Euler equation errors on every node in the state space. We then compute the maximum distance between the policy functions on any node and continue iterating until that distance falls below the tolerance criterion. We use the linear solution as an initial conjecture for the policy functions, approximate the three exogenous processes with an N-state Markov chain following Rouwenhorst (1995), and use piecewise linear interpolation to approximate future variables. See Plante et al. (2016) for a detailed description of the algorithm.

We estimate both models with data on per capita real GDP ($RGDP/CNP$), the GDP deflator (DEF), and the federal funds rate (FFR) from 1986Q1 to 2014Q2. The matrix of observables is

$$\hat{\mathrm{x}}^{data} \equiv [\log(RGDP_t/CNP_t) - \log(RGDP_{t-1}/CNP_{t-1}), \log(DEF_t/DEF_{t-1}), \log(1 + FFR_t/100)/4].$$

We calibrate five parameters (table 1). The remaining parameters are estimated with a random walk Metropolis-Hastings algorithm that uses a particle filter to compute the posterior likelihood. Following Herbst and Schorfheide (2016), we adapt the filter to include information from the current period, which helps the model match outliers during the Great Recession. The filter uses $40{,}000$ particles and systematic resampling with replacement following Kitagawa (1996). Given the simulated paths from each model, we transform the predictions for real GDP, inflation, and the policy rate according to $\hat{\mathrm{x}}_t^{model} = [\log(g_t\tilde{y}_t^{gdp}/\tilde{y}_{t-1}^{gdp}), \log(\pi_t), \log(i_t)]$. The observables contain measurement error (ME), so $\hat{\mathrm{x}}_t^{data} = \hat{\mathrm{x}}_t^{model} + \xi_t$, where $\xi \sim \mathbb{N}(0, \Sigma)$ is a vector of MEs and $\Sigma = \mathrm{diag}([\sigma^2_{me,\hat{y}}, \sigma^2_{me,\pi}, \sigma^2_{me,i}])$. The variance of each ME is set to 10% of the variance of the data (table 1). We obtain $100{,}000$ draws from the joint posterior distribution and keep every 100th draw. A detailed description of our data sources and prior distributions is provided in Plante et al. (2016).

3 Model Comparison

Table 2 reports the mean as well as the 5th and 95th percentiles of the posterior distribution for the models with Rotemberg and Calvo pricing. Interestingly, the posterior means are nearly identical for the two models. For example, the linear mapping between the two sticky price parameters, $\varphi = (\theta - 1)\omega/((1 - \bar{\beta}\omega)(1 - \omega))$, implies that our posterior mean estimate for ω is equivalent to a Rotemberg coefficient of 97.9523, which is only slightly larger than our actual posterior estimate.

Parameter	Rotemberg	Calvo	Parameter	Rotemberg	Calvo
φ/ω	96.80137 $(67.71867, 131.85091)$	0.7979 $(0.73078, 0.84921)$	ρ_g	0.20064 $(0.06547, 0.37805)$	0.21807 $(0.07278, 0.43623)$
h	0.44428 $(0.30733, 0.57745)$	0.44589 $(0.31459, 0.57800)$	ρ_β	0.90245 $(0.87001, 0.92958)$	0.91075 $(0.88074, 0.93767)$
ϕ_π	4.06383 $(3.33170, 4.90267)$	4.13917 $(3.37918, 5.07870)$	ρ_i	0.81158 $(0.75375, 0.86060)$	0.81990 $(0.75209, 0.86683)$
ϕ_y	1.49057 $(1.12702, 1.87727)$	1.46643 $(1.07218, 1.88719)$	σ_ε	0.00968 $(0.00738, 0.01241)$	0.00972 $(0.00723, 0.01248)$
$\bar{g}$	1.00376 $(1.00260, 1.00489)$	1.00367 $(1.00244, 1.00491)$	σ_υ	0.00215 $(0.00159, 0.00286)$	0.00215 $(0.00159, 0.00285)$
$\bar{\pi}$	1.00622 $(1.00556, 1.00683)$	1.00622 $(1.00564, 1.00681)$	σ_ν	0.00199 $(0.00148, 0.00261)$	0.00196 $(0.00145, 0.00257)$

Table 2: Posterior means and $(5\%, 95\%)$ credible sets of the estimated parameters

Despite the similarities in the posterior distributions, the two models do not fit the data equally well. Over the entire sample, the marginal data density in the Rotemberg model is 1506.8, whereas the density in the Calvo model is 1502.9. The exponential of the difference between those values implies a Bayes factor of 50.1, which provides strong evidence in favor of the Rotemberg model.

A useful way to understand how the dynamics differ in the two models is to compute generalized impulse responses. Figure 1 plots the responses to a 2 standard deviation (SD) positive discount factor shock, which is a proxy for a decrease in demand. We examine the responses at two different initial states of the economy: (1) the stochastic steady state (SS), where there is almost no expectation of hitting the ZLB constraint and (2) the filtered state corresponding to 2008Q4,

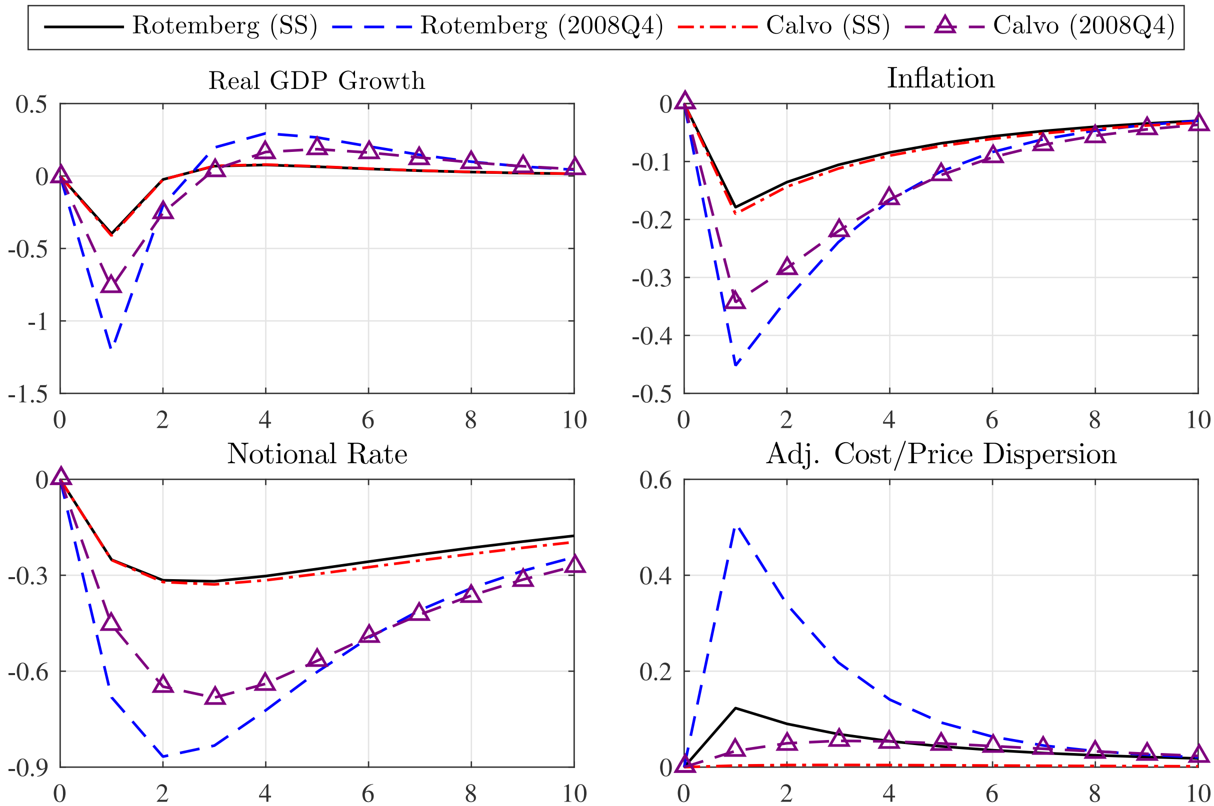

Figure 1: Impulse responses to a 2SD positive discount factor shock. The parameters are set to their posterior means.

which is when the federal funds rate first hit its ZLB constraint. When the economy begins in steady state, the reduction in demand has nearly the same effect in both models. That indicates the nonlinearities in the model, aside from the ZLB constraint, have very little effect on the economy.

There are meaningful differences between the two models when the ZLB binds. In both models, the decrease in demand leads to a larger decline in real GDP growth and inflation because the central bank cannot dampen the adverse effects of the shock by cutting its policy rate. In the Rotemberg model, the decline in real GDP growth is accentuated by the sharp increase in the price adjustment cost, which creates a wedge between output and consumption. In the Calvo model, the shock has a much more modest effect on real GDP growth and inflation. The differences stem from the fact that the quadratic price adjustment cost increases as the inflation rate diverges from its steady state, whereas the inflation rate and the markup of price over marginal cost have competing effects on the amount of price dispersion. On the one hand, the decline in demand lowers the real wage, which increases the markup and price dispersion. On the other hand, the shock lowers inflation, which reduces price dispersion. Those competing effects imply that there is a relatively small increase in price dispersion at the ZLB and a more limited adverse effect of the constraint.

The impulse responses indicate that the filtered shocks will differ when the Fed is constrained but produce similar shocks outside of the ZLB period. Figure 2 plots the median filtered shocks from the Calvo model minus those from the Rotemberg model. The differences are relative to the posterior mean estimate of the Rotemberg model's shock SD, so 0.5 means the Calvo model predicted a shock 0.5 SDs larger than the Rotemberg model. The largest differences between the two models occur from 2008Q4 to 2010Q4, which is when the notional interest rate was most

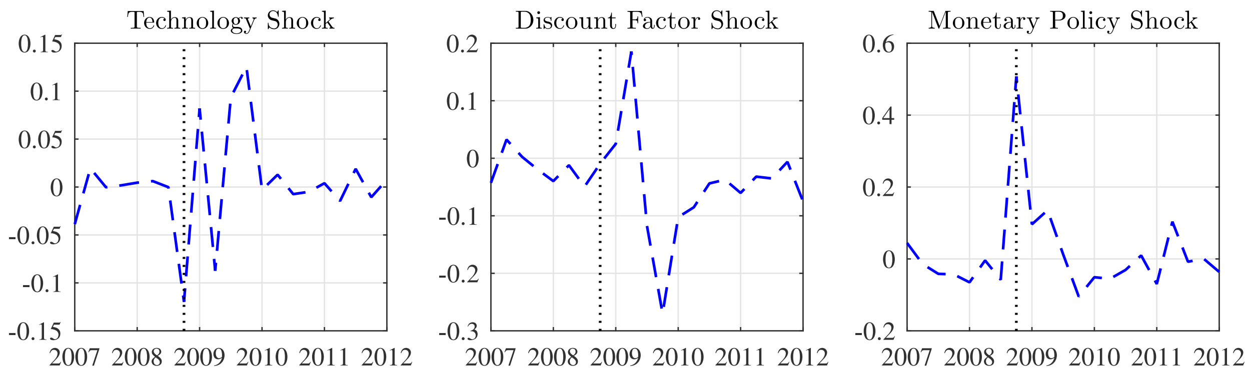

Figure 2: Median filtered shocks in the Calvo model minus the Rotemberg model. The vertical dashed line is 2008Q4.

negative and the Fed was the most constrained. For example, the Calvo model predicts a larger monetary policy shock is necessary to explain the data in 2008Q4, which is at odds with the Fed's expansionary policy. The larger policy shock compensates for the lower sensitivity in the model to demand shocks. Although the ZLB continues to bind until the end of our sample, the shocks implied by the two models are very similar after 2010Q4 since the notional rate hovered near zero.

	Rotemberg			Calvo		
	Mean	5%	95%	Mean	5%	95%
Unconditional ZLB Frequency (% of Quarters)	4.44	0.88	13.16	5.18	0.88	15.79
SS Conditional ZLB Duration (Quarters)	3.11	1.00	9.00	3.37	1.00	10.00
2008Q4 Conditional ZLB Duration (Quarters)	5.43	2.00	12.00	6.10	2.00	15.00

Table 3: Zero lower bound statistics

Two other key properties of our model are the frequency and duration of ZLB events, which are shown in table 3. To calculate those statistics, we conduct $10{,}000$ simulations for each posterior draw so the values take into account both parameter uncertainty and the distribution of shocks. The unconditional ZLB frequency is based on simulations with the same length as the data and is reported as the percent of quarters where the ZLB binds. The ZLB durations represent the number of quarters that the ZLB binds in the first ZLB event, conditional on when the economy is initialized at the stochastic steady state or the mean filtered state corresponding to 2008Q4. The Calvo model predicts a higher mean frequency of ZLB events as well as slightly longer ZLB events, but those difference are fairly insignificant since there is considerable overlap in the respective credible sets.

4 CONCLUSION

This paper estimates a nonlinear New Keynesian model with Rotemberg quadratic price adjustment costs and Calvo random price changes. The Rotemberg model has a higher marginal data density and better fits the data when the central bank is constrained. Those results indicate that the recent trend toward Rotemberg pricing is justified by the data and not just for computational convenience.

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