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ABSTRACT

We develop and estimate a general equilibrium search and matching model that accounts for key business cycle properties of macroeconomic aggregates, including labor market variables. In sharp contrast to leading New Keynesian models, we do not impose wage inertia. Instead we derive wage inertia from our specification of how firms and workers negotiate wages. Our model outperforms a variant of the standard New Keynesian Calvo sticky wage model. According to our estimated model, there is a critical interaction between the degree of price stickiness, monetary policy and the duration of an increase in unemployment benefits.

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1. Introduction

Macroeconomic models have difficulty accounting for the magnitude of business cycle fluctuations in employment and unemployment. A classic example is provided by the class of real business cycle models pioneered by Kydland and Prescott (1982).¹ Models that build on the search and matching framework of Diamond (1982), Mortensen (1982) and Pissarides (1985) also have difficulty accounting for the volatility of labor markets. For example, Shimer (2005) argues that these models can only do so by resorting to implausible parameter values.

Empirical New Keynesian models have been relatively successful in accounting for the cyclical properties of employment, by assuming that wage setting is subject to nominal rigidities.² The implied wage inertia prevents sharp, counterfactual cyclical swings in wages and inflation that would otherwise occur in these models.³ Empirical New Keynesian models have been criticized on at least four grounds. First, these models do not explain wage inertia, they simply assume it. Second, agents in the model would not choose to subject themselves to the nominal wage frictions imposed on them by the modeler.⁴ Third, empirical New Keynesian models are inconsistent with the fact that many wages are constant for extended periods of time. In practice, these models assume that agents who do not reoptimize their wage simply index it to technology growth and inflation.⁵ So, these models predict that all wages are always changing. Fourth, these models cannot be used to examine some key policy issues such as the effects of changes in unemployment benefits.⁶

We integrate search and matching models into an otherwise standard New Keynesian framework. Our models can account for the response of key macroeconomic aggregates to monetary and technology shocks. These aggregates include labor market variables like wages, employment, job vacancies and unemployment. In contrast to leading empirical New Keynesian models, we do not assume that wages are subject to exogenous nominal rigidities. Instead, we derive wage inertia as an equilibrium outcome.

As in standard New Keynesian models, we assume that price setting is subject to Calvo-style rigidities. But, guided by the micro evidence on prices, we assume that firms which do

¹See, for example, the discussion in Chetty, Guren, Manoli and Weber (2012).

²For example, Christiano, Eichenbaum and Evans (2005), Smets and Wouters (2007) and Gali, Smets and Wouters (2012) assume that nominal wages are subject to Calvo-style rigidities.

³See, for example, Christiano, Eichenbaum and Evans (2005).

⁴This criticism does not necessarily apply to a class of models initially developed by Hall (2005). We discuss these models in the conclusion.

⁵See, for example, Christiano, Eichenbaum and Evans (2005), Smets and Wouters (2007), Christiano, Trabandt and Walentin (2011a,b), and Gali, Smets and Wouters (2012).

⁶Gali (2011) provides an interpretation of the sticky wage model which has implications for unemployment, and unemployment benefits. However, that interpretation relies on the presence of pervasive union power in labor markets, an assumption that seems questionable in the United States. For additional discussion of this approach, see Galí, Smets and Wouters (2012) and Christiano (2012). The standard sticky wage model associated with Erceg, Henderson and Levin (2000) has no implications for unemployment.

not reoptimize their price must keep it unchanged, i.e. no price indexation.

One version of our model pursues a variant of Hall and Milgrom’s (2008) (henceforth HM) approach to labor markets, in which real wages are determined by alternating offer bargaining (henceforth AOB).⁷ We also consider a version of the model in which real wages are determined by a Nash bargaining sharing rule. In both versions of the model we assume, as in Pissarides (2009), that there is a fixed cost component in hiring.

We estimate the different versions of our model using a Bayesian variant of the strategy in Christiano, Eichenbaum and Evans (2005) (henceforth CEE).⁸ That strategy involves minimizing the distance between the dynamic response to monetary policy shocks, neutral technology shocks and investment-specific technology shocks in the model and the analog objects in the data. The latter are obtained using an identified vector autoregression (VAR) for 12 post-war, quarterly U.S. times series that include key labor market variables.

Both the AOB and Nash bargaining models succeed in accounting for the key features of our estimated impulse response functions. In both models, real wages have two key properties which define what we refer to as *wage inertia*. First, the real wage responds relatively little to shocks. Second, the response that does occur is very persistent. These properties are essential ingredients in the AOB and Nash bargaining model’s ability to account for the estimated response of the economy to shocks. The role of wage inertia plays a particularly important role for the dynamics of inflation. According to our VAR analysis, inflation responds very little to a monetary policy shock. The only way for the model to account for this small response is for a monetary policy shock to generate a small change in firms’ marginal costs. But that requires an inertial response of real wages. According to our VAR analysis, there is a relatively large drop in inflation after a positive neutral technology shock. Other things equal, a rise in technology drives down marginal cost and inflation in our model. Wage inertia prevents a substantial rise in real wages that would otherwise undo this downward pressure on inflation.

As it turns out, the estimated AOB model outperforms the estimated Nash bargaining model in terms of the marginal likelihood of the data. At the posterior mode of the parameters, both models generate impulse response functions that are virtually identical to each other. But, for the Nash bargaining model to match the empirical impulse response functions requires a very high replacement ratio that is extremely implausible from the perspective of our prior.⁹ In contrast, the AOB model does not require implausible parameter values to

⁷For a paper that uses a reduced form version of HM in a calibrated real business cycle model, see Hertweck (2006).

⁸We implement the Bayesian version of the CEE procedure which was developed in Christiano, Trabandt and Walentin (2011a).

⁹For a discussion of micro data which suggests that a high replacement ratio is implausible, see, for example, the discussion in Hornstein, Krusell and Violante (2010).

account for the data. Taken together, these observations explain why the marginal likelihood of the AOB model is substantially higher than that of the Nash bargaining model and why we take the former to be our benchmark search and matching model.

Wage inertia is central to the success of our AOB and Nash bargaining models. But is it a central property of a broader class of empirically successful models? To address this question, we begin by noting that in our AOB and Nash bargaining models, the real wage is the solution to a bargaining problem. The surplus sharing rules implied by these models can also be interpreted as restricted rules for setting the real wage as a function of the models' date t state variables. So, we estimate a model in which the sharing rule is replaced by a general real wage rule. The latter makes the date t real wage an unrestricted function of the model's date t state variables. Our key result is that the estimated general real wage rule does in fact satisfy wage inertia in the sense defined above. These results provide evidence in favor of the view that wage inertia is an important component of a broad class of empirically successful macro models.

How does the performance of the AOB model compare with that of the standard empirical New Keynesian model? That model incorporates Calvo wage-setting frictions along the lines developed in Erceg, Henderson and Levin (2000) (henceforth EHL). The version of the model that we emphasize does not allow for wage indexation because the resulting implications are strongly at variance with micro data on nominal wages of incumbent workers. We show that the AOB model substantially outperforms the Calvo sticky wage New Keynesian model with no wage indexation in terms of statistical fit. Specifically, the latter model does a worse job than the AOB model of accounting for the empirical impulse response functions. The Calvo sticky wage model with indexation does about as well as the AOB model in accounting for the VAR-based impulse response functions. We conclude that given the limitations of Calvo sticky wage models, there is simply no need to work with them. The AOB model fits the data at least as well and can be used to analyze a broader set of labor market variables and policy questions.

A key advantage of the AOB model is that we can use it to investigate the consequences of changes in economic policies. Specifically, we analyze the effects of an unanticipated, transitory increase in unemployment benefits, both when the zero lower bound (ZLB) on the nominal interest rate is binding and when it is not ("normal times"). In our estimated AOB model, there is a critical interaction between nominal rigidities, monetary policy and the effects of a change in unemployment benefits. In normal times, monetary policy amplifies the type of contractionary effects of an increase in unemployment benefits stressed in the flexible price models considered in the literature (see, for example, Hagedorn, Karahan, Manovskii, and Mitman, 2013). But when the ZLB binds, the contractionary effects associated with an increase in unemployment benefits are mitigated. Depending on parameter values, e.g., the

amount of time that agents expect the ZLB to bind, an increase in unemployment benefits can actually be expansionary. That said, for the empirically plausible case, the estimated AOB model implies that the effects of an increase in unemployment benefits in the ZLB are likely to be quite small.

Our paper is organized as follows. Section 2 presents our search and matching model economy. Section 3 presents the standard sticky wage model. Section 4 describes our econometric methodology. Sections 5 and 6 present the empirical results for our search and matching models, and our alternative models, respectively. Section 7 reports the results of our experiments with unemployment benefits.¹⁰ Concluding remarks appear in section 8.

2. The Model Economy

In this section we discuss our benchmark model economy. We embed search and matching labor market frictions into an otherwise standard New Keynesian model. We do so in a way that preserves the analytic tractability of the Calvo-style price setting model.¹¹

2.1. Households

The economy is populated by a large number of identical households. The representative household has a unit measure of workers which it supplies inelastically to the labor market. We denote the fraction of employed workers in the representative household in period t by l_t . An employed worker earns the nominal wage rate, W_t . An unemployed worker receives D_t goods in government-provided unemployment compensation. We assume that each worker has the same concave preferences over consumption and that households provide perfect consumption insurance, so that each worker receives the same level of consumption, C_t . The preferences of the representative household are the equally-weighted average of the preferences of its workers:

$$E_0 \sum_{t=0}^{\infty} \beta^t \ln(C_t - bC_{t-1}), \quad 0 \leq b < 1. \quad (2.1)$$

Here, b controls the degree of habit formation in preferences. The representative household's budget constraint is:

$$P_t C_t + P_{I,t} I_t + B_{t+1} \leq (R_{K,t} u_t^K - a(u_t^K) P_{I,t}) K_t + (1 - l_t) P_t D_t + W_t l_t + R_{t-1} B_t - T_t. \quad (2.2)$$

Here, T_t denotes lump sum taxes net of profits, P_t denotes the price of consumption goods, $P_{I,t}$ denotes the price of investment goods, B_{t+1} denotes one period risk-free bonds purchased

¹⁰A technical appendix is available at: sites.google.com/site/mathiastrabandt/home/downloads/CETtechapp.pdf.

¹¹For an early application of this strategy, see Walsh (2003).

in period t with gross return, R_t , and I_t denotes the quantity of investment goods. The object $R_{K,t}$, denotes the rental rate of capital services, K_t denotes the household's beginning of period t stock of capital, $a(u_t^K)$ denotes the cost, in units of investment goods, of the capital utilization rate, u_t^K and $u_t^K K_t$ denotes the household's period t supply of capital services. The functional form for the increasing and convex function, $a(\cdot)$, is described below. All prices, taxes and profits in (2.2) are in nominal terms.¹²

The representative household's stock of capital evolves as follows:

$$K_{t+1} = (1 - \delta_K) K_t + [1 - S(I_t/I_{t-1})] I_t.$$

The functional form for the increasing and convex adjustment cost function, $S(\cdot)$, is described below.

2.2. Final Good Producers

A final homogeneous good, Y_t , is produced by competitive and identical firms using the following technology:

$$Y_t = \left[\int_0^1 (Y_{j,t})^{\frac{1}{\lambda}} dj \right]^\lambda, \quad (2.3)$$

where $\lambda > 1$. The representative firm chooses specialized inputs, $Y_{j,t}$, to maximize profits:

$$P_t Y_t - \int_0^1 P_{j,t} Y_{j,t} dj,$$

subject to the production function (2.3). The firm's first order condition for the j^{th} input is:

$$Y_{j,t} = (P_t/P_{j,t})^{\frac{\lambda}{\lambda-1}} Y_t. \quad (2.4)$$

The homogeneous output, Y_t can be used to produce either consumption goods or investment goods. The production of the latter uses a linear technology in which one unit of Y_t is transformed into Ψ_t units of I_t .

2.3. Retailers

The j^{th} input good in (2.3) is produced by a *retailer*, with production function:

$$Y_{j,t} = k_{j,t}^\alpha (z_t h_{j,t})^{1-\alpha} - \phi_t. \quad (2.5)$$

The retailer is a monopolist in the product market and is competitive in factor markets. Here $k_{j,t}$ denotes the total amount of capital services purchased by firm j and ϕ_t represents

¹²In Christiano, Eichenbaum and Trabandt (2015) we argue that our model is not subject to the Chodorow-Reich and Karabarbounis (2014) critique of the setup of Hall and Milgrom (2008), which implies a highly procyclical opportunity cost of employment.

a fixed cost of production. Also, z_t is a neutral technology shock. Finally, $h_{j,t}$ is the quantity of an intermediate good purchased by the j^{th} retailer. This good is purchased in competitive markets at the price P_t^h from a *wholesaler*. As in CEE, we assume that to produce in period t , the retailer must borrow $P_t^h h_{j,t}$ at the gross nominal interest rate, R_t . The retailer repays the loan at the end of period t after receiving sales revenues. The j^{th} retailer sets its price, $P_{j,t}$, subject to the demand curve, (2.4), and the following Calvo sticky price friction (2.6):

$$P_{j,t} = \begin{cases} P_{j,t-1} & \text{with probability } \xi \\ \tilde{P}_t & \text{with probability } 1 - \xi \end{cases} . \quad (2.6)$$

Here, \tilde{P}_t denotes the price set by the fraction $1 - \xi$ of producers who can re-optimize at time t . We assume these producers make their price decision before observing the current period realization of the monetary policy shock, but after the other time t shocks. This assumption is necessary to ensure that our model satisfies the identifying assumptions that we make in our empirical work. We do not allow the non-optimizing firms to index their prices to some measure of inflation. In this way, the model is consistent with the observation that many prices remain unchanged for extended periods of time (see Eichenbaum, Jaimovich and Rebelo, 2011, and Klenow and Malin, 2011).

2.4. Wholesalers, Workers and the Labor Market

The law of motion for aggregate employment, l_t , is given by:

$$l_t = (\rho + x_t) l_{t-1}.$$

Here, ρ is the probability that a given firm/worker match continues from one period to the next. So, ρl_{t-1} denotes the number workers that were attached to firms in period $t - 1$ and remain attached at the start of period t . Also, x_t denotes the hiring rate so that $x_t l_{t-1}$ denotes the number of new firm/worker meetings at the start of period t . The number of workers searching for work at the start of period t is the sum of the number of unemployed workers in period $t - 1$, $1 - l_{t-1}$, and the number of workers that separate from firms at the end of $t - 1$, $(1 - \rho) l_{t-1}$. The probability, f_t , that a searching worker meets a firm is given by:

$$f_t = \frac{x_t l_{t-1}}{1 - \rho l_{t-1}}.$$

Wholesaler firms produce the intermediate good using labor which has a fixed marginal productivity of unity. As in Pissarides (2009), a wholesaler firm that wishes to meet a worker in period t must post a vacancy at cost s_t , expressed in units of the consumption good. The vacancy is filled with probability Q_t . In case the vacancy is filled, the firm must pay a fixed

real cost, κ_t , before bargaining with the newly-matched worker. Let J_t denote the value to the firm of a worker, expressed in units of the final good:

$$J_t = \vartheta_t^p - w_t^p. \quad (2.7)$$

Here, ϑ_t^p denotes the expected present value, over the duration of the worker/firm match, of the real intermediate good price, $\vartheta_t \equiv P_t^h/P_t$. Also, w_t^p denotes a similar present value of the real wage, $w_t \equiv W_t/P_t$. The real wage is determined by worker-firm bargaining and is discussed below. In recursive form:

$$\vartheta_t^p = \vartheta_t + \rho E_t m_{t+1} \vartheta_{t+1}^p, \quad w_t^p = w_t + \rho E_t m_{t+1} w_{t+1}^p. \quad (2.8)$$

Here, m_{t+1} is the time t household discount factor which firms and workers view as an exogenous stochastic process and is discussed below. Free entry by wholesalers implies that, in equilibrium, the expected benefit of a vacancy equals the cost:

$$Q_t (J_t - \kappa_t) = s_t. \quad (2.9)$$

Let V_t denote the value to a worker of being matched with a firm. We express V_t as the sum of the expected present value of wages earned while the match endures and the continuation value, A_t , when the match terminates:

$$V_t = w_t^p + A_t. \quad (2.10)$$

Here,

$$A_t = (1 - \rho) E_t m_{t+1} [f_{t+1} V_{t+1} + (1 - f_{t+1}) U_{t+1}] + \rho E_t m_{t+1} A_{t+1}. \quad (2.11)$$

The variable, U_t , denotes the value of being an unemployed worker :

$$U_t = D_t + \tilde{U}_t, \quad (2.12)$$

where \tilde{U}_t denotes the continuation value of unemployment:

$$\tilde{U}_t \equiv E_t m_{t+1} [f_{t+1} V_{t+1} + (1 - f_{t+1}) U_{t+1}]. \quad (2.13)$$

The vacancy filling rate, Q_t , and the job finding rate for workers, f_t , are assumed to be related to labor market tightness, Γ_t , as follows:

$$f_t = \sigma_m \Gamma_t^{1-\sigma}, \quad Q_t = \sigma_m \Gamma_t^{-\sigma}, \quad \sigma_m > 0, \quad 0 < \sigma < 1,$$

where

$$\Gamma_t = \frac{v_t l_{t-1}}{1 - \rho l_{t-1}}. \quad (2.14)$$

Here, $v_t l_{t-1}$ denotes the number of vacancies posted by firms at the start of period t .

2.5. Alternating Offer Bargaining (AOB) Model

This section describes the details of bargaining arrangements between firms and workers.¹³ At the start of period t , l_t matches are determined. At this point, each worker in l_t engages in bilateral bargaining over the current wage rate, w_t , with a wholesaler firm. Each worker/firm bargaining pair takes the outcome of all other period t bargains as given. In addition, agents have beliefs about the outcome of future wage bargains, conditional on remaining matched. Under their beliefs those future wages are not a function of current actions. Because bargaining in period t applies only to the current wage rate, we refer to it as *period-by-period bargaining*.

The periods, $t = 1, 2, \dots$ in our model represent quarters. We suppose that bargaining proceeds across M subperiods within the period, where M is even. The firm makes a wage offer at the start of the first subperiod. It also makes an offer at the start of a subsequent odd subperiod in the event that all previous offers have been rejected. Similarly, the worker makes a wage offer at the start of an even subperiod in case all previous offers have been rejected. The worker makes the last offer, which is take-it-or-leave-it.¹⁴ In subperiods $j = 1, \dots, M - 1$, the recipient of an offer has the option to accept or reject it. If the offer is rejected the recipient may declare an end to the negotiations or he may plan to make a counteroffer at the start of the next subperiod. In the latter case there is a probability, δ , that bargaining breaks down. We now explain the bargaining in detail.

Consider a firm that makes a wage offer, $w_{j,t}$, in subperiod $j < M$, j odd. The firm sets $w_{j,t}$ as low as possible subject to the worker not rejecting it. The resulting wage offer, $w_{j,t}$, satisfies the following indifference condition:

$$V_{j,t} = \max \{U_{j,t}, \delta U_{j,t} + (1 - \delta) [D_t/M + V_{j+1,t}]\}. \quad (2.15)$$

We assume that when an agent is indifferent between accepting and rejecting an offer, he accepts it. The left hand side of (2.15), $V_{j,t}$, denotes the value to a worker of accepting the wage offer $w_{j,t}$:

$$V_{j,t} = w_{j,t} + \tilde{w}_t^p + A_t. \quad (2.16)$$

Here, \tilde{w}_t^p denotes the present discounted value of the future wages that workers and firms believe will prevail while their match endures:

$$\tilde{w}_t^p = \rho E_t m_{t+1} w_{t+1}^p. \quad (2.17)$$

¹³A well known feature of bargaining models is that equilibrium outcomes depend on the specification of what happens out of equilibrium. This dependence is a feature of many models. Examples include models of debt and strategic models of monetary policy, as well as models of strategic interactions between firms.

¹⁴Here our bargaining environment differs from that of HM. The latter assume that bargaining can in principle go on forever, so that there is no last offer.

In (2.16) and (2.17), \tilde{w}_t^p and A_t are taken as given by the period t worker-firm bargaining pair.

The right hand side of (2.15) is the maximum, over the worker's outside option, $U_{j,t}$, and the worker's *disagreement payoff*. The latter is the value of a worker who rejects a wage offer with the intention of making a counteroffer in the next subperiod. We assume the disagreement payoff exceeds the outside option, though in practice this must be verified. The first term in the disagreement payoff reflects that the negotiations break down with probability δ , in which case the worker reverts to his outside option, with value $U_{j,t}$:

$$U_{j,t} = \frac{M - j + 1}{M} D_t + \tilde{U}_t.$$

Here, \tilde{U}_t is defined in (2.13). Also, the term multiplying D_t reflects our assumption that the worker receives unemployment benefits in period t in proportion to the number of subperiods spent in non-employment. The second term in the disagreement payoff reflects the fact that with probability $1 - \delta$ the worker receives unemployment benefits, D_t/M , and then makes a counteroffer $w_{j+1,t}$ to the firm which he (correctly) expects to be accepted.

Next, consider the problem of a worker who makes an offer in subperiod, j , where $j < M$ and j is even. The worker offers the highest possible wage, $w_{t,j}$, subject to the firm not rejecting it. The resulting wage offer, $w_{j,t}$, satisfies the following indifference condition:

$$J_{j,t} = \max \{0, \delta \times 0 + (1 - \delta) [-\gamma_t + J_{j+1,t}]\}. \quad (2.18)$$

The left hand side of (2.18) denotes the value to a firm of accepting the wage offer $w_{j,t}$:

$$J_{j,t} = \frac{M - j + 1}{M} \vartheta_t + \tilde{\vartheta}_t^p - (w_{j,t} + \tilde{w}_t^p), \quad (2.19)$$

where

$$\tilde{\vartheta}_t^p = \rho E_t m_{t+1} \vartheta_{t+1}^p. \quad (2.20)$$

The term multiplying ϑ_t in (2.19) reflects our assumption that a worker produces $1/M$ intermediate goods in each subperiod during which production occurs.

The expression on the right of the equality in (2.18) is the maximum over the firm's outside option (i.e., zero) and its disagreement payoff. We assume the firm's disagreement payoff exceeds its outside option, though in practice this must be verified. If the firm rejects the worker's offer with the intention of making a counteroffer there is a probability, δ , that negotiations break down and both the worker and firm are sent to their outside options. With probability $1 - \delta$ the firm makes a counteroffer, $w_{j+1,t}$, in the next subperiod which it (correctly) expects to be accepted. To make a counteroffer, the firm incurs a real cost, γ_t . The second expression in the square bracketed term in (2.18) is the value associated with a successful firm counteroffer, $w_{j+1,t}$.

Finally, consider subperiod M in which the worker makes the final, take-it-or-leave-it offer. The worker chooses the highest possible wage subject to the firm not rejecting it, which leads to the following indifference condition:

$$J_{M,t} = 0. \quad (2.21)$$

Here, $J_{M,t}$ is (2.19) with $j = M$.

We now discuss the solution to the bargaining game. To this end, it is useful to note that $w_{j,t}$ and \tilde{w}_t^p always appear as a sum in the indifference conditions, (2.15) and (2.18) (see (2.16) and (2.19)). Define,

$$w_{j,t}^p \equiv w_{j,t} + \tilde{w}_t^p, \quad (2.22)$$

for $j = 1, \dots, M$. We obtain $w_{M,t}^p$ by solving (2.21):

$$w_{M,t}^p = \vartheta_t/M + \tilde{\vartheta}_t^p.$$

Then, (2.15) for $j = M - 1$ can be solved for w_{M-1}^p and (2.18) can be solved for w_{M-2}^p .¹⁵ In this way, the indifference conditions can be solved uniquely to obtain:

$$w_{1,t}^p, w_{2,t}^p, w_{3,t}^p, \dots, w_{M,t}^p, \quad (2.23)$$

conditional on variables that are exogenous to the worker-firm bargaining pair. The solution to the bargaining problem, w_t^p , is just $w_{1,t}^p$. The linearity of the indifference conditions gives rise to a simple closed-form expression for the solution:¹⁶

$$w_t^p = \frac{1}{\alpha_1 + \alpha_2} [\alpha_1 \vartheta_t^p + \alpha_2 (U_t - A_t) + \alpha_3 \gamma_t - \alpha_4 (\vartheta_t - D_t)], \quad (2.24)$$

where

$$\begin{aligned} \alpha_1 &= 1 - \delta + (1 - \delta)^M, \quad \alpha_2 = 1 - (1 - \delta)^M, \\ \alpha_3 &= \alpha_2 \frac{1 - \delta}{\delta} - \alpha_1, \quad \alpha_4 = \frac{1 - \delta}{2 - \delta} \frac{\alpha_2}{M} + 1 - \alpha_2. \end{aligned}$$

It can be shown that $\alpha_1, \alpha_2, \alpha_3$ and α_4 , are strictly positive.

It is useful to observe that after rearranging the terms in (2.24) and making use of (2.7) and (2.10), (2.24) can be written as follows:

$$J_t = \beta_1 (V_t - U_t) - \beta_2 \gamma_t + \beta_3 (\vartheta_t - D_t), \quad (2.25)$$

with $\beta_i = \alpha_{i+1}/\alpha_1$, for $i = 1, 2, 3$. We refer to (2.25) as the *Alternating Offer Bargaining sharing rule*.

¹⁵Recall our assumption that disagreement payoffs are no less than outside options.

¹⁶See the technical appendix for a detailed derivation.

It is a standard result that the solution to the finite horizon AOB game is unique. Consistent with this observation, we see that for given \tilde{w}_t^p , ϑ_t , ϑ_t^p , U_t , A_t , D_t , the real wage is uniquely determined by

$$w_t = w_t^p - \tilde{w}_t^p, \quad (2.26)$$

where w_t^p is defined in (2.24). In effect, we have defined a mapping from beliefs about future wages, summarized in \tilde{w}_t^p , to the present actual wage, w_t . We only consider equilibria in which the current actual wage and the believed future wages are the same time invariant functions of the contemporaneous state of the economy.

2.6. Nash Bargaining Model

It will be useful to contrast the quantitative implications of our model with one in which wages are determined according to a Nash sharing rule. Specifically, we define the *Nash Bargaining model* as the version of our model in which we replace the AOB sharing rule, (2.25) with the *Nash sharing rule*:

$$J_t = \frac{1 - \eta}{\eta} (V_t - U_t). \quad (2.27)$$

Here, η is the share of total surplus, $J_t + V_t - U_t$, received by the worker. The bargaining solution in both the Nash and AOB models takes the form of a static sharing rule. However, the two sharing rules are not nested. The Nash sharing rule obviously does not nest the AOB sharing rule. More subtly, the AOB sharing rule does not nest the Nash sharing rule. The reason is that, in general, for a given η in (2.27), one cannot find M , δ , γ such that $\beta_1 = (1 - \eta) / \eta$ and $\beta_2 = \beta_3 = 0$.¹⁷ The non-nested nature of the sharing rules is the reason that we treat the two models as distinct.

2.7. Present Value Bargaining

The equilibrium allocations associated with period-by-period bargaining can also be supported by an alternative bargaining arrangement, which we call *present value bargaining*. Under this arrangement, a given firm/worker pair bargains only once, over w_t^p , when they first meet. It is straightforward to verify that if they pursue AOB, then the w_t^p that they agree on satisfies (2.24) or, equivalently, (2.25). Under Nash bargaining, w_t^p satisfies (2.27). Under these respective bargaining arrangements it is immaterial to the firms and workers how exactly the period by period wage rate is paid out, so long as it is consistent with the

¹⁷Binmore, Rubenstein and Wolinsky (1986) describe a class of environments in which the Nash bargaining solution is the solution to AOB bargaining. Our bargaining environment is different and the Nash solution is nested in the AOB solution only in the special case, $\eta = 1/2$. In this case, as $M \rightarrow \infty$, $\gamma, \delta \rightarrow 0$, $\gamma/\delta \rightarrow 0$, $(1 - \delta)^M \rightarrow 0$, then $\beta_1 \rightarrow 1$, $\beta_2, \beta_3 \rightarrow 0$. For $\eta \neq 1/2$ we have not been able to find M, γ, δ such that $\beta_1 = (1 - \eta) / \eta$ and $\beta_2 = \beta_3 = 0$.

agreed-upon w_t^p . For example, in one scenario workers and firms simply agree to the constant flow nominal wage rate that is consistent with w_t^p .¹⁸ In this scenario, the only workers that experience a wage change is the subset that start new jobs.

A potential problem with present value bargaining is that not all the state contingent wage payments that are consistent with an agreed-upon w_t^p are time consistent. For example, consider a scenario in which $w_t = w_t^p$ and the wage rate is zero thereafter. If bargaining were re-opened at a later date, the worker would no longer have an incentive to accept the previously agreed-upon zero wage rate. That is, in general present value bargaining requires strong assumptions about agents' ability to commit. Under period by period bargaining we are able to avoid these assumptions. Moreover, w_t is uniquely determined so it is straightforward to incorporate wage data into our analysis.

2.8. Market Clearing, Monetary Policy and Functional Forms

Market clearing in intermediate goods and in the services of capital require,

$$\int_0^1 h_{j,t} dj = l_t, \quad u_t^K K_t = \int_0^1 k_{j,t} dj,$$

respectively. Market clearing for final goods requires:

$$C_t + (I_t + a(u_t^K)K_t)/\Psi_t + (s_t/Q_t + \kappa_t)x_t l_{t-1} + G_t = Y_t, \quad (2.28)$$

where G_t denotes government consumption.

Perfect competition in the production of investment goods implies that the nominal price of investment goods equals the corresponding marginal cost:

$$P_{I,t} = P_t/\Psi_t.$$

Equality between the demand for loans by retailers, $h_t P_t^h$, and the supply by households, B_{t+1}/R_t , requires:

$$h_t P_t^h = B_{t+1}/R_t.$$

The asset pricing kernel, m_{t+1} , is constructed using the marginal contribution of consumption to discounted utility, which we denote by λ_t :

$$m_{t+1} = \beta \lambda_{t+1}/\lambda_t.$$

We adopt the following specification of monetary policy:

$$\ln(R_t/R) = \rho_R \ln(R_{t-1}/R) + (1 - \rho_R) [r_\pi \ln(\pi_t/\bar{\pi}) + r_y \ln(\mathcal{Y}_t/\mathcal{Y}_t^*)] + \sigma_R \varepsilon_{R,t}.$$

¹⁸See Pissarides (2009) and Shimer (2004) for a closely related discussion in simple search and matching models with no nominal frictions.

Here, $\bar{\pi}$ denotes the monetary authority's inflation target. The monetary policy shock, $\varepsilon_{R,t}$, has unit variance and zero mean. Also, R is the steady state value of R_t . The variable, \mathcal{Y}_t , denotes Gross Domestic Product (GDP):

$$\mathcal{Y}_t = C_t + I_t/\Psi_t + G_t,$$

and \mathcal{Y}_t^* denotes the value of \mathcal{Y}_t along the non-stochastic steady state growth path.

Working with the data from Fernald (2012) we find that the growth rate of total factor productivity is well described by an *i.i.d.* process. Accordingly, we assume that $\ln \mu_{z,t} \equiv \ln(z_t/z_{t-1})$ is *i.i.d.* We also assume that $\ln \mu_{\Psi,t} \equiv \ln(\Psi_t/\Psi_{t-1})$ follows a first order autoregressive process. The parameters that control the standard deviations of the innovations in both processes are denoted by $(\sigma_z, \sigma_{\Psi})$, respectively. The autocorrelation of $\ln \mu_{\Psi,t}$ is denoted by ρ_{Ψ} .

The sources of growth in our model are neutral and investment-specific technological progress. Let:

$$\Phi_t = \Psi_t^{\frac{\alpha}{1-\alpha}} z_t. \quad (2.29)$$

To guarantee balanced growth in the nonstochastic steady state, we require that each element in $[\phi_t, s_t, \kappa_t, \gamma_t, G_t, D_t]$ grows at the same rate as Φ_t in steady state. To this end, we adopt the following specification:¹⁹

$$[\phi_t, s_t, \kappa_t, \gamma_t, G_t, D_t]' = [\phi, s, \kappa, \gamma, G, D]' \Omega_t. \quad (2.30)$$

Here, Ω_t is defined as follows:

$$\Omega_t = \Phi_{t-1}^{\theta} (\Omega_{t-1})^{1-\theta}, \quad (2.31)$$

where $0 < \theta \leq 1$ is a parameter to be estimated. With this specification, Ω_t/Φ_{t-1} converges to a constant in nonstochastic steady state. When θ is close to zero, Ω_t is virtually unresponsive in the short-run to an innovation in either of the two technology shocks, a feature that we find attractive on *a priori* grounds. Given the specification of the exogenous processes in the model, $Y_t/\Phi_t, C_t/\Phi_t, w_t/\Phi_t$ and $I_t/(\Psi_t\Phi_t)$ converge to constants in nonstochastic steady state.

We assume that the cost of adjusting investment takes the form:

$$S(I_t/I_{t-1}) = \frac{1}{2} \left(\exp \left[\sqrt{S''} (I_t/I_{t-1} - \mu \times \mu_{\Psi}) \right] + \exp \left[-\sqrt{S''} (I_t/I_{t-1} - \mu \times \mu_{\Psi}) \right] \right) - 1.$$

Here, μ and μ_{Ψ} denote the unconditional growth rates of Φ_t and Ψ_t . The value of I_t/I_{t-1} in nonstochastic steady state is $(\mu \times \mu_{\Psi})$. In addition, S'' denotes the second derivative of $S(\cdot)$, evaluated at steady state. The object, S'' , is a parameter to be estimated. It is straightforward to verify that $S(\mu \times \mu_{\Psi}) = S'(\mu \times \mu_{\Psi}) = 0$.

¹⁹Our specification follows Christiano, Trabandt and Walentin (2012) and Schmitt-Grohé and Uribe (2012).

We assume that the cost associated with setting capacity utilization is given by:

$$a(u_t^K) = \sigma_a \sigma_b (u_t^K)^2 / 2 + \sigma_b (1 - \sigma_a) u_t^K + \sigma_b (\sigma_a / 2 - 1)$$

where σ_a and σ_b are positive scalars. For a given value of σ_a we select σ_b so that the steady state value of u_t^K is unity. The object, σ_a , is a parameter to be estimated.

3. The Calvo Sticky Wage Model

We now describe a medium-sized DSGE model which incorporates the Calvo sticky wage framework of EHL. The final homogeneous good, Y_t , is produced by competitive and identical firms using the technology, (2.3). The representative final good producer buys the j^{th} specialized input, $Y_{j,t}$, from a monopolist who produces the input using the technology, (2.5). Capital services are purchased in competitive rental markets. In (2.5), $h_{j,t}$ now refers to the quantity of a homogeneous labor input that the monopolist purchases from a representative labor contractor. The representative contractor produces the homogeneous labor input by combining differentiated labor inputs, $l_{i,t}$, $i \in (0, 1)$, using the technology:

$$h_t = \left[\int_0^1 (l_{i,t})^{\frac{1}{\lambda_w}} di \right]^{\lambda_w}, \quad \lambda_w > 1. \quad (3.1)$$

Labor contractors are perfectly competitive and take the nominal wage rate, W_t , of h_t as given. They also take the wage rate, $W_{i,t}$, of the i^{th} labor type as given. Profit maximization on the part of contractors implies:

$$l_{i,t} = (W_t / W_{i,t})^{\frac{\lambda_w}{\lambda_w - 1}} h_t. \quad (3.2)$$

There is a continuum of households, each indexed by $i \in (0, 1)$. The i^{th} household is the monopoly supplier of $l_{i,t}$ and chooses $W_{i,t}$ subject to (3.2) and Calvo wage-setting frictions. That is, the household optimizes the wage, $W_{i,t}$, with probability $1 - \xi_w$. With probability ξ_w the wage rate is given by:

$$W_{i,t} = W_{i,t-1}. \quad (3.3)$$

Note that we do not allow for indexation when households do not reoptimize.

With two exceptions, the i^{th} household's budget constraint is given by (2.2). First, $D_t = 0$. Second, we replace $l_t W_t$ by $l_{i,t} W_{i,t} + A_{i,t}$. Here, $A_{i,t}$ represents the net proceeds of an asset that provides insurance against the idiosyncratic uncertainty associated with the Calvo wage-setting friction. Apart from employment and $A_{i,t}$, the other choice variables in (2.2) need not be indexed by i because of household access to insurance and our specification of preferences:

$$\ln(C_t - bC_{t-1}) - \varkappa \frac{l_{i,t}^{1+\psi}}{1+\psi}, \quad \varkappa > 0, \psi \geq 0. \quad (3.4)$$

4. Econometric Methodology

We estimate our model using a Bayesian variant of the strategy in CEE that minimizes the distance between the dynamic response to three shocks in the model and the analog objects in the data. The latter are obtained using an identified VAR for post-war quarterly U.S. times series that include key labor market variables. The particular Bayesian strategy that we use is the one developed in Christiano, Trabandt and Walentin (2011a) (henceforth CTW).

To facilitate comparisons, our analysis is based on the same VAR as used in CTW who estimate a 14 variable VAR using quarterly data that are seasonally adjusted and cover the period 1951Q1 to 2008Q4. As in CTW, we identify the dynamic responses to a monetary policy shock by assuming that the monetary authority sees the contemporaneous values of all the variables in the VAR and a monetary policy shock affects only the Federal Funds Rate contemporaneously. As in Altig, Christiano, Eichenbaum and Linde (2011), Fisher (2006) and CTW, we make two assumptions to identify the dynamic responses to the technology shocks: (i) the only shocks that affect labor productivity in the long-run are the innovations to the neutral technology shock, z_t , and the innovation to the investment-specific technology shock, Ψ_t and (ii) the only shock that affects the price of investment relative to consumption in the long-run is the innovation to Ψ_t . These identification assumptions are satisfied in our model. Standard lag-length selection criteria lead CTW to work with a VAR with 2 lags.²⁰

We include the following variables in the VAR:²¹ $\Delta \ln(\text{relative price of investment})$, $\Delta \ln(\text{real } GDP/\text{hours})$, $\Delta \ln(\text{GDP deflator})$, unemployment rate, $\ln(\text{capacity utilization})$, $\ln(\text{hours})$, $\ln(\text{real } GDP/\text{hours}) - \ln(\text{real wage})$, $\ln(\text{nominal } C/\text{nominal } GDP)$, $\ln(\text{nominal } I/\text{nominal } GDP)$, $\ln(\text{vacancies})$, job separation rate, job finding rate, $\ln(\text{hours}/\text{labor force})$, Federal Funds rate.

Given an estimate of the VAR we can compute the implied impulse response functions to the three structural shocks. We stack the contemporaneous and 14 lagged values of each of these impulse response functions for 12 of the VAR variables in a vector, $\hat{\psi}$. We do not include the job separation rate and the size of the labor force because our model assumes those variables are constant. We include these variables in the VAR to ensure the VAR results are not driven by an omitted variable bias.

The logic underlying our model estimation procedure is as follows. Suppose that our structural model is true. Denote the true values of the model parameters by θ_0 . Let $\psi(\theta)$ denote the model-implied mapping from a set of values for the model parameters to the analog impulse responses in $\hat{\psi}$. Thus, $\psi(\theta_0)$ denotes the true value of the impulse responses

²⁰See CTW for a sensitivity analysis with respect to the lag length of the VAR.

²¹See the technical appendix in CTW for details about the data.

whose estimates appear in $\hat{\psi}$. According to standard classical asymptotic sampling theory, when the number of observations, T , is large, we have

$$\sqrt{T} \left(\hat{\psi} - \psi(\theta_0) \right) \overset{a}{\sim} N(0, W(\theta_0, \zeta_0)).$$

Here, ζ_0 denotes the true values of the parameters of the shocks in the model that we do not formally include in the analysis. Because we solve the model using a log-linearization procedure, $\psi(\theta_0)$ is not a function of ζ_0 . However, the sampling distribution of $\hat{\psi}$ is a function of ζ_0 . We find it convenient to express the asymptotic distribution of $\hat{\psi}$ in the following form:

$$\hat{\psi} \overset{a}{\sim} N(\psi(\theta_0), V), \quad (4.1)$$

where

$$V \equiv W(\theta_0, \zeta_0) / T.$$

For simplicity our notation does not make the dependence of V on θ_0, ζ_0 and T explicit. We use a consistent estimator of V . Motivated by small sample considerations, this estimator has only diagonal elements (see CTW). The elements in $\hat{\psi}$ are graphed in Figures 1 – 3 (see the solid lines). The gray areas are centered, 95 percent probability intervals computed using our estimate of V .

In our analysis, we treat $\hat{\psi}$ as the observed data. We specify priors for θ and then compute the posterior distribution for θ given $\hat{\psi}$ using Bayes' rule. This computation requires the likelihood of $\hat{\psi}$ given θ . Our asymptotically valid approximation of this likelihood is motivated by (4.1):

$$f(\hat{\psi}|\theta, V) = (2\pi)^{-\frac{N}{2}} |V|^{-\frac{1}{2}} \exp \left[-0.5 \left(\hat{\psi} - \psi(\theta) \right)' V^{-1} \left(\hat{\psi} - \psi(\theta) \right) \right]. \quad (4.2)$$

The value of θ that maximizes the above function represents an approximate maximum likelihood estimator of θ . It is approximate for three reasons: (i) the central limit theorem underlying (4.1) only holds exactly as $T \rightarrow \infty$, (ii) our proxy for V is guaranteed to be correct only for $T \rightarrow \infty$, and (iii) $\psi(\theta)$ is calculated using a linear approximation.

Treating the function, f , as the likelihood of $\hat{\psi}$, it follows that the Bayesian posterior of θ conditional on $\hat{\psi}$ and V is:

$$f(\theta|\hat{\psi}, V) = \frac{f(\hat{\psi}|\theta, V) p(\theta)}{f(\hat{\psi}|V)}. \quad (4.3)$$

Here, $p(\theta)$ denotes the prior distribution of θ and $f(\hat{\psi}|V)$ denotes the marginal density of $\hat{\psi}$:

$$f(\hat{\psi}|V) = \int f(\hat{\psi}|\theta, V) p(\theta) d\theta.$$

The mode of the posterior distribution of θ can be computed by maximizing the value of the numerator in (4.3), since the denominator is not a function of θ . We compute the posterior distribution of the parameters using a standard Monte Carlo Markov chain (MCMC) algorithm.

We evaluate the relative empirical performance of different models by comparing their implication for the marginal likelihood of $\hat{\psi}$. To compute a marginal likelihood, we use Geweke’s modified harmonic mean procedure. For an analysis of the validity of this approach to comparing models, see Inoue and Shintani (2015).

In part of our analysis, we find it convenient to compute the marginal likelihood of a subset, $\hat{\psi}_1$, of the elements in $\hat{\psi}$ (see the technical appendix for details). The latter computation requires integrating $f(\hat{\psi}|V)$ with respect to the elements of $\hat{\psi}$ not in $\hat{\psi}_1$. To this end, we find it convenient to make use of the Laplace approximation of $f(\hat{\psi}|V)$. Below, we provide evidence of the accuracy of the Laplace approximation for computing the marginal likelihood.

5. Empirical Results for Search and Matching Models

In this section we present the empirical results for our search and matching models. The first subsection discusses the *a priori* restrictions that we impose on the models. The next two subsections report estimation results for the AOB and Nash Bargaining models, respectively.

5.1. Parameter and Steady State Restrictions

Some model parameter values were set *a priori*. See Panel A of Table 1. We specify β so that the steady state annual real rate of interest is 3 percent. The depreciation rate on capital, δ_K , is set to imply an annual depreciation rate of 10 percent. The values of μ and μ_{Ψ} are determined by the sample average of real per capita GDP and real investment growth. We set the parameter M to 60, which roughly corresponds to the number of business days in a quarter. This assumption is consistent with HM, who assume that it takes one day to counter an offer. We set $\rho = 0.9$ which implies a match survival rate that is consistent with the values used in HM, Shimer (2012a) and Walsh (2003). We discuss the parameters, ξ_w and λ_w , which pertain to the sticky wage model, below.

We choose values for five model parameters, σ_m , γ , ϕ , G , $\bar{\pi}$, so that, conditional on the other parameters, the model satisfies the five steady state targets listed in Panel B, Table 1. Following den Haan, Ramey and Watson (2000) and Ravenna and Walsh (2008), the target for the steady state vacancy filling rate, Q , is 0.7. The steady state unemployment rate is 5.5 percent which corresponds to the average unemployment rate in our sample. The profits

of wholesalers are zero in steady state, the steady state ratio of government consumption to gross output is 0.2, and steady state inflation, π , is 2.5 percent.

5.2. AOB Model Results

Table 3 reports the mean and 95 percent probability intervals for the priors and posteriors of the parameters in the AOB model. Several features are worth noting. First, the posterior mode of ξ implies a reasonable degree of price stickiness, with prices changing on average once every four quarters.

Second, the posterior mode of δ implies that there is a roughly 0.2 percent chance of an exogenous break-up in negotiations when a wage offer is rejected. Our estimate of δ is somewhat lower than HM's calibrated value of δ of 0.55 percent.

Third, the posterior mode of our model parameters imply that it costs roughly 0.6 of one day's revenue for a firm to prepare a counteroffer to a worker (see the bottom of Table 2).

Fourth, the fixed cost component of hiring accounts for the lion's share of the total cost of meeting a worker. Table 3 reports the posterior mode values of:

$$\eta_s = \frac{svl}{Y}, \quad \eta_h = \frac{\kappa xl}{Y}.$$

Here, η_s and η_h denote the share of vacancy posting costs and hiring fixed costs to gross output in steady state, respectively. The fixed cost component of meeting a worker, expressed as a percent of the total cost is:²²

$$\frac{\eta_h}{\eta_h + \eta_s} = 0.94.$$

The importance of hiring fixed costs is consistent with micro evidence reported in Yashiv (2000), Cheremukhin and Restrepo-Echavarria (2010) and Carlsson, Eriksson and Gottfries (2013).²³

Fifth, in steady state the total cost associated with hiring a new worker is roughly 7 percent of the wage rate. That is:

$$\frac{\frac{s}{Q} + \kappa}{w} = \frac{\eta_s + \eta_h}{1 - \rho} \frac{Y}{wl} = 0.068.$$

Silva and Toledo (2009) report that, depending on the exact costs included, the value of this statistic is between 4 and 14 percent, a range that encompasses our estimate.

²²Here, we have used the facts, $v = x/Q$ and that the cost of meeting a worker is, by (2.9), equal to $s/Q + \kappa$.

²³Using different models estimated on macro data of various countries, Christiano, Trabandt and Walentin (2011b), Furlanetto and Goshenny (2012) and Justiniano and Michelacci (2011) also conclude that hiring fixed costs are important relative to the vacancy posting cost.

Sixth, the prior mode of the replacement ratio, D/w , is roughly 0.4. Based on studies of unemployment insurance, HM report a range of estimates for the replacement ratio between 0.1 and 0.4. Based on their summary of the literature, Gertler, Sala and Trigari (2008) argue that a plausible upper bound for the replacement ratio is 0.7 when one takes informal sources of insurance into account. Our prior mode for D/w is roughly in the middle of all these estimates. According to Table 3 the prior and posterior distributions of D/w are quite similar. We interpret this result as indicating that the replacement ratio does not play a critical role in the AOB model's ability to account for the data. A corollary of this result is that identification of D/w must come from microeconomic data.

Seventh, the posterior mean of θ which governs the responsiveness of $[\phi_t, \kappa_t, \gamma_t, G_t, s_t, D_t]$ to technology shocks, is small (0.05) and the associated probability interval is quite tight. So, these variables are quite unresponsive in the short-run to technology shocks. A large value of θ would make γ_t and D_t rise by more after a positive technology shock. But, this would imply a larger rise in the real wage rate and induce counterfactual implications for hours worked and inflation.

Eighth, the posterior mode of the parameters governing monetary policy are similar to those reported in the literature (see for example Christiano, Trabandt and Walentin, 2011a).

Ninth, the point estimate of the markup is roughly 42 percent, which is higher than the 20 percent estimate in the benchmark model reported in CEE, which assumes dynamic price indexation. By that we mean, firms which do not reoptimize their current period price adjust that price by the aggregate inflation rate realized in the previous period. In contrast, the point estimate of the markup is roughly 40 percent when CEE estimate a version of their model with static price indexation. By that we mean, firms which do not reoptimize their current period price adjust that price by the steady state inflation rate. This version of the model seems most comparable to ours, in which there is no indexation at all.

The solid black lines in Figures 1 - 3 display VAR-based estimates of impulse responses to a monetary policy shock, a neutral technology shock and an investment-specific technology shock, respectively. The grey areas represent 95 percent probability intervals. The solid lines with the circles correspond to the impulse response functions of the AOB model evaluated at the posterior mode of the estimated parameters.

Figure 1 shows that the AOB model does reasonably well at reproducing the estimated effects of an expansionary monetary policy shock, including the hump-shaped rise of real GDP and hours worked, as well as the muted response of inflation. Notice that real wages respond by less than hours to the monetary policy shock. Even though the maximal rise in hours worked is roughly 0.13 percent, the maximal rise in real wages is only 0.08 percent. Significantly, the model accounts for the hump-shaped fall in the unemployment rate as well as the rise in the job finding rate and vacancies that follow in the wake of an expansionary

monetary policy shock. The model does understate the rise in the capacity utilization rate. The sharp rise of capacity utilization in the estimated VAR may reflect that our capacity utilization rate data pertains to the manufacturing sector, which may overstate the average response across all sectors in the economy.

The basic intuition for how a monetary policy shock affects the economy in the AOB model is as follows. As in standard New Keynesian models, an expansionary monetary policy shock drives the real interest rate down, inducing an increase in the demand for final goods. This rise induces an increase in the demand for the output of sticky price retailers. Since they must satisfy demand, the retailers purchase more of the wholesale good. Therefore, the relative price of the wholesale good increases and the marginal revenue product, ϑ_t , associated with a worker rises. Other things equal, this rise motivates wholesalers to hire more workers and thus increases the probability that an unemployed worker finds a job. The latter effect induces a rise in workers' disagreement payoffs. The resulting increase in workers' bargaining power generates a rise in the real wage. Given our estimated parameter values, alternating offer bargaining generates a moderate increase in real wages, a large rise in employment, a substantial decline in unemployment, and a small rise in inflation. If there was a large, persistent rise in the real wage, the model would generate a counterfactually large rise in inflation. The reason is that real wages are a key component of firms' real marginal costs. Firms that have a chance to reset prices set those prices as an increasing function of current and expected future real marginal cost. So, to account for the observed cyclical behavior of inflation it is critical for the model to generate small cyclical movements in marginal cost.

From Figure 2 we see that the model also does a good job of accounting for the estimated effects of a neutral technology shock. Of particular note is that the model reproduces the estimated sharp fall in the inflation rate that occurs after a positive neutral technology shock.²⁴ For inflation to fall sharply, there must be a sharp drop in marginal cost. This in turn requires that the rise in the real wage that occurs after a technology shock is small. As Figure 2 shows, the AOB model has this property. Below, we argue that the ability to account for the sharp fall in inflation after a technology shock is useful for discriminating between different models. Also, the model generates a sharp fall in the unemployment rate along with a large rise in job vacancies and the job finding rate. So, the estimated AOB model is not subject to Shimer's (2005) critique of search and matching models with low replacement rates.

Finally, Figure 3 shows that the model also does a good job of accounting for the estimated response of the economy to an investment-specific technology shock.

²⁴For additional evidence that inflation responds more strongly to technology shocks than to monetary policy shocks, see Paciello (2011).

5.3. Nash Bargaining Model Results

When we estimated the Nash Bargaining model, the resulting impulse response functions are virtually identical to the ones implied by the estimated AOB model. For this reason, we do not report the Nash Bargaining model’s impulse response functions in Figures 1 - 3. Priors and posteriors for the model parameters are reported in Table 3. With one important exception, the posterior mode values of the parameters that the Nash Bargaining and AOB models share in common are basically the same. The important exception is the replacement ratio, D/w . The posterior mode for D/w is 0.88 in the Nash Bargaining model, versus 0.37 in the AOB model. In both cases, the posterior probability intervals are very tight, with no overlap. Two other parameter estimates come out slightly different: the curvature on the capacity utilization adjustment cost function, σ_a , and the share of hiring fixed cost, η_h .

There is a substantial 14 log point difference in the marginal likelihood between the two models because the Nash Bargaining model must reach far into the right tail of the prior distribution for D/w to match the impulse response functions. To explain this it is convenient to work with the Laplace approximation of the marginal likelihood because it involves a simple product of the likelihood and the prior, evaluated at the posterior mode. As noted before, this approximation appears to be an excellent one in our application. Let \mathcal{L} denote the log of the Laplace approximation of the marginal likelihood of the data:

$$\mathcal{L} = \ln f\left(\hat{\psi}|\theta^*, V\right) - \ln \left[(2\pi)^{-N} |G_{\theta\theta}(\theta^*)|^{1/2} \right] + \ln p(\theta^*), \quad (5.1)$$

where θ^* denotes the mode of the posterior distribution of θ and $G_{\theta\theta}$ denotes the Hessian of the log posterior distribution, evaluated at θ^* .²⁵ The other variables in (5.1) are defined in section 4.

We compute (5.1) for both the AOB model and the Nash Bargaining model. It turns out that the log likelihoods, $\ln f\left(\hat{\psi}|\theta^*, V\right)$, of the two models are essentially the same: 344.6 and 343.9 in the case of the AOB and Nash Bargaining model, respectively. The object in square brackets in (5.1) turns out to be also roughly the same for the two models. Thus, the 14 log point gap between the AOB and Nash Bargaining models is due to the difference in the prior term, $\ln p$, evaluated at posterior modes, θ^* , of the two models. Most of that difference is due to the implausibly high value of D/w (0.88) that the Nash Bargaining model needs to account for the data.

The high value of D/w is critical to the performance of the Nash Bargaining model. To make this observation precise we begin by re-calculating the impulse response functions implied by the Nash Bargaining model making only one change: we re-parameterize the replacement ratio, D/w , from 0.88 to 0.37, where the latter value is posterior mode of D/w

²⁵See, for example, Christiano, Trabandt and Walentin (2011a).

in the estimated AOB model. The dashed lines in Figures 4 - 6 are the impulse response functions corresponding to this re-parameterized Nash Bargaining model while the solid lines with circles depict the impulse responses of the Nash bargaining model evaluated at the estimated posterior mode with D/w equal 0.88.

Figure 4 shows that this one change leads to a dramatic deterioration in the performance of the Nash bargaining model. All of the quantity variables like hours worked, real GDP as well as unemployment are now much less responsive to a monetary policy shock. In contrast, the real wage and inflation respond by too much relative to the VAR-based impulse response functions. Figures 5 and 6 reveal a similar pattern with respect to the technology shocks. Consistent with the results in Shimer (2005), the Nash bargaining model with the lower replacement ratio generates very small changes in the unemployment rate after a neutral technology shock. Significantly, this version of the model also generates counterfactually large movements in inflation. However these shortcomings are remedied by a higher value of D/w . With respect to unemployment, this finding is reminiscent of Hagedorn and Manovskii's (2008) argument that a high replacement ratio has the potential to boost the volatility of unemployment and vacancies in search and matching models with Nash Bargaining.

To further assess the role played by D/w , we re-estimated the Nash Bargaining model holding the value of D/w fixed at 0.37. The marginal likelihood of the Nash Bargaining model with $D/w = 0.37$ is a dramatic 126 log points lower than the marginal likelihood in the estimated AOB model.²⁶ The dashed - dotted lines in Figures 4 - 6 correspond to the impulse response functions associated with this version of the Nash Bargaining model. Figure 4 indicates that this model cannot account for the rise in output, hours worked, consumption, investment, vacancies and the job finding rate that occur after an expansionary monetary policy shock. Just as importantly, the model implies that real wages rise in a counterfactual manner after such a shock. While less dramatic, Figures 5 and 6 show that the model's performance with respect to the technology shocks also deteriorates. Taken together, our results indicate that empirically plausible versions of the Nash Bargaining model must assume a very high value of D/w .

6. Assessing the Search and Matching Models Against Alternatives

In our search and matching model, the real wage is the solution to a bargaining problem, the implications of which are fully summarized in the sharing rule. The next subsection reports the results of estimating our model with a reduced form sharing rule that nests the AOB and Nash sharing rules as special cases. The second subsection below reports the results of replacing the sharing rule with two alternative wage rules: i) a general wage rule that makes

²⁶The full set of parameter estimates is available upon request from the authors.

the date t real wage a log-linear function of all of the model's date t state variables, and ii) motivated by the results in i) we consider an easy-to-interpret simple wage rule which summarizes the key characteristics of the general wage rule. In the final subsection, we consider how the performance of our model compares with that of the standard empirical New Keynesian model with Calvo sticky wages.

6.1. The Reduced Form Sharing Rule Model

Consider the following reduced form sharing rule:

$$J_t = \epsilon_1 (V_t - U_t) - \epsilon_2 \Omega_t + \epsilon_3 (\vartheta_t - D_t), \quad (6.1)$$

where Ω_t is defined in (2.31). We define the *reduced form sharing rule model* as the version of our model in which the sharing rule is given by (6.1) and the ϵ_i 's are unrestricted. The reduced form sharing rule model nests, as special cases, the AOB and Nash models. In the AOB model, $\epsilon_1 = \beta_1$, $\epsilon_2 = \beta_2 \gamma$, $\epsilon_3 = \beta_3$. Here, $\beta_1, \beta_2, \beta_3$ are the functions of δ and M defined after (2.25). In the Nash model, $\epsilon_1 = (1 - \eta)/\eta$, $\epsilon_2 = \epsilon_3 = 0$. By comparing the estimated values of the sharing rule coefficients of the three models we can assess the plausibility of the Nash and AOB models.

To maximize the impact of the data on inference about the ϵ_i 's, we adopt uniform priors on these parameters. The upper (lower) bound of the uniform distribution is 3 times (-1 times) the mode of the posterior distribution on ϵ_i , $i = 1, 2, 3$, when we estimate the AOB model. We estimate the model with the reduced form sharing rule using the same priors for the other parameters as in the estimated AOB model (see Table 3). Our results are reported in Table 4.²⁷

Panels A and B report the mode and a 95 percent probability interval implied by the posterior distribution of ϵ_1 , ϵ_2 and ϵ_3 in the AOB and Nash models, respectively. Denote the mode of these distributions by ϵ_i^x , for $x = AOB, Nash$, $i = 1, 2, 3$. Panel C reports a measure of closeness of the ϵ_i^x 's to the corresponding posterior distribution implied the reduced form sharing rule model. We use the p -value as our measure of closeness. Thus, according to panel C in Table 4, $prob[\epsilon_i > \epsilon_i^{AOB}]$ is between 0.21 and 0.24 for $i = 1, 2, 3$. So, the sharing rule parameters implied by the AOB model are quite plausible relative to the posterior distribution implied by the reduced form sharing rule model.

In contrast, the Nash model does very poorly by this metric. Specifically, $prob[\epsilon_1 > \epsilon_1^{Nash}]$ is essentially zero. Thus, the sharing parameters implied by the Nash model are extremely implausible under the posterior distribution implied by the generalized sharing rule model. This last result corroborates our findings, based on the marginal likelihood, that the AOB model provides a better statistical fit of the data than the Nash model.

²⁷A full set of parameter estimates is available upon request from the authors.

6.2. General Wage Rule Model

While more general than the Nash and AOB sharing rules, equation (6.1) might still be quite restrictive. Accordingly, we also consider a reduced form model in which the date t real wage is assumed to be a log-linear function of all date t state variables of the AOB model. We treat the coefficients on the state variables as free parameters to be estimated.

Let \bar{w}_t denote the real wage scaled by Φ_t :

$$\bar{w}_t \equiv w_t/\Phi_t. \quad (6.2)$$

Here, Φ_t denotes the combination of neutral and investment-specific technology shocks defined in (2.29). The state variables of the model include $R_{t-1}, k_{t-1} = K_{t-1}/(\Psi_{t-1}\Phi_{t-1}), l_{t-1}, \Omega_{t-1}, c_{t-1} = C_{t-1}/\Phi_{t-1}, i_{t-1} = I_{t-1}/(\Psi_{t-1}\Phi_{t-1}), \mu_{z,t}, \mu_{\Psi,t}, p_{t-1}^*$.²⁸ Let,

$$\begin{aligned} \ln \bar{w}_t = & \text{constant} + \varkappa_1 \ln R_{t-1} + \varkappa_2 \ln k_{t-1} + \varkappa_3 \ln l_{t-1} + \varkappa_4 \ln p_{t-1}^* \\ & + \varkappa_5 \ln \Omega_{t-1} + \varkappa_6 \ln c_{t-1} + \varkappa_7 \ln i_{t-1} + \varkappa_8 \ln \mu_{z,t} + \varkappa_9 \ln \mu_{\Psi,t}. \end{aligned} \quad (6.3)$$

We define the *general wage rule model* as the version of our model in which the wage is determined by (6.3). Table 5 reports the posterior mode and probability interval of the coefficients $\varkappa_i, i = 1, \dots, 9$ in the log-linearized representation of the general wage rule.²⁹ The marginal likelihood is roughly 20 log points higher than the one for the estimated AOB model. Figure 7 displays the impulse response functions of unemployment, inflation and the real wage to our three shocks.³⁰ Notice that wages and inflation respond somewhat more to a monetary policy shock in the AOB model than in the general wage rule model. This difference helps to explain the lower marginal likelihood associated with the AOB model. It also illustrates the crucial role that real wages play in determining the response of inflation to a monetary policy shock. Specifically, the reason that the response of inflation is stronger in the AOB model than in the general wage rule model is because the real wage response is stronger. Figure 7 also shows that the dynamic responses of the AOB and general wage rule models to technology shocks are very similar.

We infer from Figure 7 that the general wage rule has two key features. First, the real wage responds relatively little to shocks. Second, the response that does occur is very persistent. Any successful account of the data will have to somehow account for those features.

²⁸Here, p_t^* denotes the measure of price dispersion across retailers, which captures the effects of resource misallocation due to price-setting frictions (see Yun, 1996). In particular, $p_t^* = (P_t^*/P_t)^{\frac{\lambda}{1-\lambda}}$ where $P_t^* = \left[\int_0^1 P_{i,t}^{\frac{\lambda}{1-\lambda}} di \right]^{\frac{1-\lambda}{\lambda}}$ and $P_t = \left[\int_0^1 P_{i,t}^{\frac{1}{1-\lambda}} di \right]^{1-\lambda}$.

²⁹The constant term in (6.3) is adjusted so that, conditional on the other model parameters, the steady unemployment rate is 5.5 percent.

³⁰A complete set of impulse response functions is available upon request from the authors.

6.3. Simple Wage Rule Model

Next, we work with the following simple – easy-to-interpret – rule for the real wage, which in principle has the ability to capture the two key features of the general wage rule discussed in the previous section:

$$\ln \bar{w}_t = \text{constant} + \iota_1 \ln \bar{w}_{t-1} + \iota_2 \ln l_{t-1} + \iota_3 \ln \mu_{z,t} + \iota_4 \ln \mu_{\Psi,t}. \quad (6.4)$$

We define the *simple wage rule model* as the version of our model in which the wage is determined by (6.4). The definition of \bar{w}_t in (6.2) implies that the impact on $\ln w_t$ of an innovation in $\ln z_t$ and in $\ln \Psi_t$ is $1 + \iota_3$ and $1 + \iota_4 \alpha / (1 - \alpha)$, respectively. So, negative values of ι_3 and ι_4 imply less than complete pass-through from technology shocks to the real wage in the period of the shock. High values of ι_1 ensure that the incomplete pass-through persists over time. Finally, note that we exclude the time t shock to monetary policy in (6.4) in order to be consistent with the identifying assumptions in our VAR analysis. Monetary policy does affect w_t dynamically through $\ln l_{t-1}$. Other things equal, we anticipate a low value of ι_2 because the estimated response of w_t to a monetary policy shock is persistently small.

Table 5 reports the posterior mode and probability interval of the coefficients ι_i , $i = 1, \dots, 4$ in the simple wage rule.³¹ Four things are worth noting. First, the data are quite informative about the coefficients, ι_i , $i = 1, \dots, 4$, in the sense that, in each case, the posterior probability interval is much smaller than the prior probability interval. Second, as anticipated, the posterior mode for ι_1 is quite large. Third, the posterior mode for ι_2 is small. Finally, the posterior modes for ι_3 and ι_4 are negative.

According to Table 5, the marginal likelihoods for the simple wage rule model and the general wage rule model are very similar. It is evident that the impulse response functions of the general wage rule model and the simple wage rule model are very similar. We interpret these two observations as supporting the notion that the simple wage rule succinctly captures the key features of the general wage rule.

We conclude this section by addressing the question: “If the simple wage rule is a good description of the data, why bother with structural models like the AOB model?” First, it is important to recall that the AOB model does capture the key features of both wage rule models. Second, it is important to be clear about the limitations of the wage rule models. For example, these models cannot be used to study the effects of policy interventions such as a change in unemployment benefits. From the perspective of the AOB and the Nash models, the coefficients in the wage rule models, including the constants, depend on objects like the

³¹The constant term in (6.4) is adjusted so that, conditional on the other model parameters, the steady unemployment rate is 5.5 percent.

level of unemployment benefits, D . The wage rule models are silent on how these coefficients vary in response to changes in policy.

Finally, one could in principle reinterpret our wage rules as a wage norms in the sense of Hall (2005). Even with this interpretation it would be difficult to use the model to analyze the effects of policy changes. For example, one would have to verify that the wage produced by the general wage rule does not induce the worker or the firm to walk away from the match. If the implied wage did not satisfy this condition the model would be silent about the resulting implications.

6.4. Calvo Sticky Wage Model

In this subsection we discuss the empirical properties of the Calvo sticky wage model and compare its performance to the AOB model. Recall that our Calvo sticky wage model rules out indexation of wages to technology and inflation. We comment on a version of the model that allows for such indexation at the end of this subsection.

Table 1 reports parameter values of the sticky nominal wage model that we set *a priori*. Note in particular that we fix ξ_w to 0.75 so that nominal wages change on average once a year.³² Table 3 reports the posterior modes of the estimated sticky wage model parameters. Figures 1 - 3 show that with two important exceptions, the Calvo sticky wage model does reasonably well at accounting for the estimated impulse response functions. These exceptions are that the model substantially understates the response of inflation to a neutral technology shock and, to a somewhat lesser extent, to a monetary policy shock.

We now compare the marginal likelihood of the AOB model with that of the Calvo sticky wage model. Doing so is complicated by the fact that the two models do not address the same data. For example, the Calvo sticky wage model has no implications for vacancies and the job finding rate. To obtain a measure of fit based on a common data set, we integrate out unemployment, the job finding rate and vacancies from the marginal likelihood associated with the AOB model. As discussed in section 4, the integration is performed on the Laplace approximation of the posterior distribution. The marginal likelihoods based on the impulse response functions of the nine remaining variables are reported in Table 3 (see “Laplace, 9 Observables”). The marginal likelihood for the AOB model is about 60 log points higher than it is for the Calvo sticky wage model. We conclude that, subject to the approximations that we used to compute the marginal likelihood function, there is substantial statistical evidence in favor of the AOB model relative to the Calvo sticky wage model. The evidence reported in the table suggests that the Laplace approximation is quite accurate in our setting. To see this, note that the marginal likelihood for the 12 variable

³²We encountered numerical problems in calculating the posterior mode of model parameters when we did not place a dogmatic prior on ξ_w .

system based on the Laplace approximation is essentially the same as the marginal likelihood based on MCMC simulations. This result holds for both the AOB and Nash models.

We also estimated a version of the Calvo sticky wage model where we allow for wage indexation. In particular, we assume that if a labor supplier cannot re-optimize his wage then it changes by the steady state growth rate of output times the lagged inflation rate. The impulse response functions of the AOB model and the Calvo sticky wage model with indexation are qualitatively very similar. The marginal likelihood of the latter model about 3 log points higher than that of the AOB model. Overall, we conclude that the performance of the two models is similar. But, the performance of the Calvo sticky wage model depends very much on the troubling wage indexation assumption.

7. The Dynamic Effects of a Change in Unemployment Benefits

In this section we investigate the implications of our estimated AOB model for changes in unemployment benefits. We look at these implications when benefits are changed when the zero lower bound (ZLB) on nominal interest is binding and when it is not (i.e. in “normal times”). According to our estimated model, price setting frictions and monetary policy play a key role in determining the response of the economy to a change in unemployment benefits, D . Our key findings are as follows. First, in normal times, a rise in D increases the value of being unemployed, so that the real wage rises, aggregate economic activity falls and the unemployment rate rises.³³ Second, other things equal, when the ZLB is binding a rise in D gives rise to countervailing expansionary forces. If those forces are sufficiently strong, a rise in D can in principle lead to an economic expansion. Third, whether we are in the ZLB or in normal times, the effects of a rise in D depend very much on how sticky prices are. Specifically, the effects of a change in D are smaller the stickier prices are, i.e., the larger is ξ . Fourth, our estimated AOB model implies that a one percent increase in D that lasts roughly 2 years has a contractionary effect when the economy is not in the ZLB. The same increase has essentially no effect when the economy is in the ZLB.

7.1. A Rise in Unemployment Benefits in Normal Times

We investigate the effects of an unanticipated, transitory increase in unemployment benefits using the estimated version of our AOB model. The specific experiment that we perform is as follows. We suppose that the economy is in nonstochastic steady state and is expected to remain there indefinitely. In period $t = 0$ there is an unanticipated jump in unemployment benefits. Thereafter, there are no further shocks. Agents correctly understand that unem-

³³These effects are qualitatively similar to those documented in Hagedorn, Karahan, Manovskii and Mitman (2013) in a flexible price search and matching model with Nash bargaining.

ployment benefits will revert back to steady state. We replace D in (2.30) by d_t in time $t = 0$, where

$$\ln d_{t+1} = (1 - \rho_D) \ln D + \rho_G \ln d_t,$$

for $t = 0, 1, 2, \dots$. We set $d_0 > D$ so that the ratio of D_0 to the unshocked steady state value of w_0 jumps from its initial steady state value of 0.37 to 0.38. We consider two values of ρ_D , 0.75 and 0.90. The time needed to close 90 percent of the gap between d_t and D in these two cases is roughly two and five years, respectively. The first row of Figure 8 reports the dynamic impact of the shock to d_0 on unemployment for the estimated AOB model. Recall that the mode of the posterior distribution for the price stickiness parameter, ξ , is 0.75. Since the effects of a change in unemployment benefits depend in an interesting way on the parameter ξ , we also report results for a version of the model where $\xi = 0.5$, so that prices are less sticky (see row 2).

Row 1 in Figure 8 shows that, in normal times, the increase in unemployment benefits leads to a relatively small, but persistent, increase in the unemployment rate. The intuition for this result is straightforward. In normal times, a rise in unemployment benefits increases the value of unemployment so that real wages rise. That rise has two effects. First, it reduces the incentive of firms to post vacancies. This standard contractionary effect is the one that is stressed in the literature (see, for example, Hagedorn, Karahan, Manovskii and Mitman, 2013). The second effect reflects the presence of price-setting frictions in our model. These frictions have the consequence that the rise in the real wage leads to an increase in inflation. These frictions also imply that the response of monetary policy to inflation has an impact on economic activity. Specifically, our estimated monetary policy rule has the property that the nominal interest rate rises by more than inflation. The resulting rise in the real interest rate drives spending on goods and services down, thus magnifying the decline in aggregate economic activity induced by the rise in unemployment benefits.

Figure 8 shows that the magnitude of the rise unemployment after the increase is increasing in ρ_D and decreasing in ξ . The larger is ρ_D , the more the value of unemployment rises with an increase in d_0 , so the standard contractionary effect stressed in the literature is larger. The smaller is ξ , i.e. the more flexible prices are, the larger is the immediate effect on inflation of a given rise in the real wage. Since it is the one-period inflation rate that enters the monetary policy rule, the more flexible prices are, the larger is the increase in the nominal interest rate associated with an increase in d_0 . So, the magnitude of the second effect (i.e. the real interest rate effect) discussed above is larger.

7.2. A Rise in Unemployment Benefits When the ZLB Binds

We now consider the effects of the same rise in d_0 studied in the previous section, with one modification. The ZLB is binding in period $t = 0$, when the shock occurs. We do not explicitly model why the ZLB is binding. Instead we simply assume that the nominal interest rate is fixed at its steady state value for x quarters after $t = 0$. We consider two cases, $x = 4, 8$.³⁴ This choice is motivated by results in Swanson and Williams (2014), who argue that, during the period 2009Q1-2012Q4, professional forecasters expected the ZLB to be binding between one and two years. In our experiments we assume that after the ZLB ceases to bind, policy reverts to our estimated interest rate rule.

We use the same two mechanisms discussed above to describe the dynamic effects of the increase in unemployment benefits. The standard contractionary effect - which raises the real wage and reduces firms' incentive to post vacancies - is still present. However the second effect, which is based on the interaction of price setting frictions and monetary policy, operates very differently when the ZLB is binding. As before, the increase in real wages leads to a rise in inflation. But, with a fixed nominal interest rate the rise in inflation leads to a fall in the real interest rate. That fall drives spending on goods and services up. So, when the ZLB is binding the model embodies forces that, other things equal, lead to an expansion in economic activity after an increase in unemployment benefits. These expansionary forces are stronger the longer the ZLB is expected to bind relative to the duration of the increase in unemployment benefits. To understand this point, suppose that the bulk of the increased benefits occurs after $t = x$, i.e., after the ZLB ceases to bind. The logic of the previous section applies and the economy experiences a recession after $t = x$. Internalizing this fact, forward looking agents spend less in the ZLB than they would have otherwise.³⁵ Finally, these expansionary forces are also stronger the more flexible prices are, conditional on the ZLB binding.³⁶

Columns 2 and 3 in Figure 8 report our results for $x = 4$ and 8, respectively. Recall that row 1 corresponds to the estimated AOB model. Note that when $\rho_D = 0.75$, the standard contractionary effect and the effects stemming from the price setting frictions in the ZLB roughly cancel. So, the net effect of an increase in unemployment benefits in the ZLB is roughly zero. Consistent with our discussion above, when $\rho_D = 0.9$ and $x = 4$ the contractionary effect of an increase in unemployment benefits dominates and there is a positive, albeit small, rise in unemployment. Also consistent with the discussion above,

³⁴We obtain an exact solution to the nonlinear equilibrium conditions of the model using the extended path method (see, for example, Christiano, Eichenbaum and Trabandt, 2015).

³⁵The reasoning here is similar to the logic in Christiano, Eichenbaum and Rebelo's (2011) discussion of the dependence of the government spending multiplier on the duration of the ZLB and the duration of an increase in government spending.

³⁶This phenomenon is also discussed in Christiano, Eichenbaum and Rebelo (2011) and Werning (2012).

when $\rho_D = 0.9$ and $x = 8$, the responses are shifted down. So, there is a small fall in unemployment for the first year after the increase in benefits, followed by a small rise in unemployment. Finally, row 2 shows that the more flexible prices are, the larger are the effects stemming from price setting frictions. We conclude that, from the perspective of our model, there is a critical interaction between the degree of price stickiness, monetary policy and the duration of an increase in unemployment benefits.

We are keenly aware that our model does not capture some potentially important effects of unemployment compensation. Specifically, our model abstracts from heterogeneity among agents so that we cannot address the impact of an increase in the amount of time that agents are eligible for unemployment benefits. Pursuing this would expand the number of labor market states in the model and it would substantially complicate the worker-firm bargaining problem.³⁷ Finally, we have also abstracted from liquidity constraints, and we have assumed complete insurance against labor market outcomes. We leave these important extensions to future research.

8. Conclusion

This paper constructs and estimates an equilibrium business cycle model which can account for the response of the U.S. economy to neutral and investment-specific technology shocks as well as monetary policy shocks. The focus of our analysis is on how labor markets respond to these shocks. Significantly, our model does not assume that wages are sticky. Instead, we derive inertial wages from our specification of how firms and workers interact when negotiating wages. This inertia can be interpreted as applying to the period-by-period wage, or to the present value of the wage package negotiated at the time that a worker and firm first meet.

We have been critical of standard sticky wage models in this paper. Still, Hall (2005) describes one interesting line of defense for sticky wages. He introduces sticky wages into the search and matching framework in a way that satisfies the condition that no worker-employer pair has an unexploited opportunity for mutual improvement (Hall, 2005, p. 50). A sketch of Hall's logic is as follows: in a model with labor market frictions, there is a gap between the reservation wage required by a worker to accept employment and the highest wage a firm is willing to pay an employee. This gap, or bargaining set, fluctuates with the shocks that affect the surplus enjoyed by the worker and the employer. When calibrated based on aggregate data, the fluctuations in the bargaining set are sufficiently small and the width of the set is sufficiently wide, that an exogenously sticky wage rate can remain inside the

³⁷For interesting work on this issue in a flexible price setting, see Costain and Reiter (2008) and Hagedorn, Karahan, Manovskii and Mitman (2013).

set for an extended period of time. Gertler and Trigari (2009) and Shimer (2012b) pursue this idea in a calibrated model while Gertler, Sala and Trigari (2008) do so in an estimated, medium-sized DSGE model.³⁸ A concern about this strategy for justifying sticky wages is that the microeconomic shocks which move actual firms' bargaining sets are far more volatile than what the aggregate data suggest. As a result, it may be harder to use the preceding approach to rationalize sticky wages than had initially been recognized.

We wish to emphasize that our approach follows HM in assuming that the cost of disagreement in wage negotiations is relatively insensitive to the state of the business cycle. This assumption played a key role in the empirical success of our model. Assessing the empirical plausibility of this assumption using microeconomic data is a task that we leave to future research.

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³⁸See also Krause and Lubik (2007), Christiano, Ilut, Motto and Rostagno (2008), Thomas (2008), Gali (2010) and Christiano, Trabandt and Walentin (2011b).

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Table 1: Non-Estimated Parameters and Calibrated Variables

Parameter	Value	Description
<i>Panel A: Parameters</i>		
δ_K	0.025	Depreciation rate of physical capital
β	0.9968	Discount factor
ρ	0.9	Job survival probability
M	60	Max. bargaining rounds per quarter (alternating offer model)
λ_w	1.2	Wage markup parameter (Calvo sticky wage model)
ξ_w	0.75	Wage stickiness (Calvo sticky wage model)
$400\ln(\mu)$	1.7	Annual output per capita growth rate
$400\ln(\mu \cdot \mu_\Psi)$	2.9	Annual investment per capita growth rate
<i>Panel B: Steady State Values</i>		
$400(\pi - 1)$	2.5	Annual net inflation rate
<i>profits</i>	0	Intermediate goods producers profits
Q	0.7	Vacancy filling rate
u	0.055	Unemployment rate
G/Y	0.2	Government consumption to gross output ratio

Table 2: Steady States and Implied Parameters at Estimated Posterior Mode in Structural Alternating Offer Bargaining and Nash Bargaining Models

Variable	Alternating Offer Bargaining	Nash Bargaining	Description
K/Y	7.35	6.64	Capital to gross output ratio (quarterly)
C/Y	0.56	0.58	Consumption to gross output ratio
I/Y	0.24	0.21	Investment to gross output ratio
l	0.945	0.945	Steady state labor input
R	1.014	1.014	Gross nominal interest rate (quarterly)
R^{real}	1.0075	1.0075	Gross real interest rate (quarterly)
mc	0.70	0.70	Marginal cost (inverse markup)
σ_b	0.036	0.036	Capacity utilization cost parameter
Y	1.18	1.06	Gross output
f	0.63	0.63	Job finding rate
ϑ	0.91	0.84	Marginal revenue of wholesaler
x	0.1	0.1	Hiring rate
J	0.06	0.07	Value of firm
V	271.2	258.4	Value of work
U	270.4	258.2	Value of unemployment
v	0.14	0.14	Vacancy rate
w	0.90	0.84	Real wage
$\bar{\pi}$	2.5	2.5	Inflation target (annual percent)
ϕ/Y	0.42	0.43	Fixed cost to gross output ratio
σ_m	0.66	0.66	Level parameter in matching function
η	-	0.67	Total surplus share received by workers
$\gamma/(\vartheta/M)$	0.59	-	Counteroffer costs as share of daily revenue

Table 3: Priors and Posteriors of Parameters: Structural Wage Setting Models

	Alternating Offer Bargaining	Nash Bargaining	Calvo Sticky Wages ^a	
Prior Distribution	Posterior Distribution			
$\mathcal{D}, \text{Mode}, [2.5-97.5\%]$	$\text{Mode}, [2.5-97.5\%]$			
<i>Price Setting Parameters</i>				
Price Stickiness, ξ	$\mathcal{B}, \mathbf{0.68}, [0.45 \ 0.84]$	$\mathbf{0.75}, [0.69 \ 0.78]$	$\mathbf{0.74}, [0.69 \ 0.79]$	$\mathbf{0.74}, [0.67 \ 0.77]$
Price Markup Parameter, λ	$\mathcal{G}, \mathbf{1.19}, [1.11 \ 1.31]$	$\mathbf{1.42}, [1.33 \ 1.51]$	$\mathbf{1.43}, [1.35 \ 1.52]$	$\mathbf{1.24}, [1.14 \ 1.31]$
<i>Monetary Authority Parameters</i>				
Taylor Rule: Smoothing, ρ_R	$\mathcal{B}, \mathbf{0.76}, [0.37 \ 0.94]$	$\mathbf{0.84}, [0.81 \ 0.87]$	$\mathbf{0.84}, [0.82 \ 0.87]$	$\mathbf{0.77}, [0.75 \ 0.81]$
Taylor Rule: Inflation, r_π	$\mathcal{G}, \mathbf{1.69}, [1.42 \ 2.00]$	$\mathbf{1.38}, [1.21 \ 1.65]$	$\mathbf{1.38}, [1.23 \ 1.69]$	$\mathbf{2.02}, [1.82 \ 2.39]$
Taylor Rule: GDP, r_y	$\mathcal{G}, \mathbf{0.08}, [0.03 \ 0.22]$	$\mathbf{0.03}, [0.01 \ 0.07]$	$\mathbf{0.04}, [0.02 \ 0.08]$	$\mathbf{0.01}, [0.00 \ 0.02]$
<i>Preferences and Technology Parameters</i>				
Consumption Habit, b	$\mathcal{B}, \mathbf{0.50}, [0.21 \ 0.79]$	$\mathbf{0.80}, [0.78 \ 0.84]$	$\mathbf{0.81}, [0.78 \ 0.84]$	$\mathbf{0.68}, [0.65 \ 0.74]$
Capacity Utilization Adj. Cost, σ_a	$\mathcal{G}, \mathbf{0.32}, [0.09 \ 1.23]$	$\mathbf{0.11}, [0.04 \ 0.30]$	$\mathbf{0.18}, [0.05 \ 0.32]$	$\mathbf{0.03}, [0.01 \ 0.16]$
Investment Adjustment Cost, S''	$\mathcal{G}, \mathbf{7.50}, [4.57 \ 12.4]$	$\mathbf{15.7}, [11.0 \ 19.6]$	$\mathbf{15.2}, [10.7 \ 19.0]$	$\mathbf{5.03}, [4.15 \ 7.95]$
Capital Share, α	$\mathcal{B}, \mathbf{0.33}, [0.28 \ 0.38]$	$\mathbf{0.26}, [0.20 \ 0.27]$	$\mathbf{0.23}, [0.21 \ 0.27]$	$\mathbf{0.33}, [0.27 \ 0.34]$
Technology Diffusion, θ	$\mathcal{B}, \mathbf{0.50}, [0.13 \ 0.87]$	$\mathbf{0.05}, [0.02 \ 0.07]$	$\mathbf{0.03}, [0.01 \ 0.05]$	$\mathbf{0.04}, [0.02 \ 0.86]$
<i>Labor Market Parameters</i>				
Prob. Bargaining Breakup, 100δ	$\mathcal{G}, \mathbf{0.18}, [0.04 \ 1.53]$	$\mathbf{0.19}, [0.09 \ 0.37]$		
Replacement Ratio, D/w	$\mathcal{B}, \mathbf{0.39}, [0.21 \ 0.60]$	$\mathbf{0.37}, [0.22 \ 0.63]$	$\mathbf{0.88}, [0.85 \ 0.90]$	
Hiring Fixed Cost / Output, $100\eta_h$	$\mathcal{G}, \mathbf{0.91}, [0.50 \ 1.67]$	$\mathbf{0.46}, [0.24 \ 0.84]$	$\mathbf{0.64}, [0.34 \ 1.07]$	
Vacancy Cost / Output, $100\eta_s$	$\mathcal{G}, \mathbf{0.05}, [0.01 \ 0.28]$	$\mathbf{0.03}, [0.00 \ 0.12]$	$\mathbf{0.02}, [0.00 \ 0.09]$	
Matching Function Parameter, σ	$\mathcal{B}, \mathbf{0.50}, [0.31 \ 0.69]$	$\mathbf{0.55}, [0.47 \ 0.61]$	$\mathbf{0.54}, [0.47 \ 0.61]$	
Inverse Labor Supply Elasticity, ψ	$\mathcal{G}, \mathbf{0.94}, [0.57 \ 1.55]$			$\mathbf{0.92}, [0.33 \ 1.01]$
<i>Exogenous Processes Parameters</i>				
Std. Dev. Monetary Policy, $400\sigma_R$	$\mathcal{G}, \mathbf{0.65}, [0.56 \ 0.75]$	$\mathbf{0.63}, [0.57 \ 0.70]$	$\mathbf{0.63}, [0.58 \ 0.70]$	$\mathbf{0.64}, [0.57 \ 0.71]$
Std. Dev. Neutral Tech., $100\sigma_{\mu_z}$	$\mathcal{G}, \mathbf{0.08}, [0.03 \ 0.22]$	$\mathbf{0.16}, [0.11 \ 0.19]$	$\mathbf{0.14}, [0.11 \ 0.18]$	$\mathbf{0.32}, [0.28 \ 0.35]$
Std. Dev. Invest. Tech., $100\sigma_\Psi$	$\mathcal{G}, \mathbf{0.08}, [0.03 \ 0.22]$	$\mathbf{0.12}, [0.08 \ 0.15]$	$\mathbf{0.11}, [0.08 \ 0.16]$	$\mathbf{0.15}, [0.12 \ 0.19]$
AR(1) Invest. Technology, ρ_Ψ	$\mathcal{B}, \mathbf{0.75}, [0.53 \ 0.92]$	$\mathbf{0.72}, [0.60 \ 0.85]$	$\mathbf{0.74}, [0.59 \ 0.83]$	$\mathbf{0.57}, [0.44 \ 0.66]$
<i>Memo Items</i>				
Log Marginal Likelihood (MCMC, 12 Observables):		286.7	272.9	
Log Marginal Likelihood (Laplace, 12 Observables):		286.5	272.6	
Log Marginal Likelihood (MCMC, 9 Observables ^b):				262.6
Log Marginal Likelihood (Laplace, 9 Observables):		321.1	306.9	262.3

Notes: For model specifications where particular parameter values are not relevant, the entries in this table are blank. Posterior mode and parameter distributions are based on a standard MCMC algorithm with a total of 10 million draws (11 chains, 50 percent of draws used for burn-in, draw acceptance rates about 0.24). \mathcal{B} and \mathcal{G} denote beta and gamma distributions, respectively.

^a Calvo sticky wage model as in Erceg, Henderson and Levin (2000).

^b Dataset excludes unemployment, vacancies and job finding rates.

Table 4: AOB, Nash vs. Reduced Form Sharing Rule at Posterior Modes

Sharing Rule: $J_t = \epsilon_1 (V_t - U_t) - \epsilon_2 \Omega_t + \epsilon_3 (\vartheta_t - D_t)$			
<i>Panel A: Alternating Offer Bargaining (AOB) Sharing Rule^a</i>			
	ϵ_1	ϵ_2	ϵ_3
Posterior Mode	0.06	0.28	0.47
95% Probability Interval	[0.03 0.12]	[0.13 0.35]	[0.44 0.49]
<i>Panel B: Nash Bargaining Sharing Rule^b</i>			
	ϵ_1	ϵ_2	ϵ_3
Posterior Mode	0.48	0	0
95% Probability Interval	[0.28 0.88]	-	-
<i>Panel C: Reduced Form Sharing Rule^c</i>			
Reduced Form Sharing Rule vs. AOB	$p(\epsilon_1 > 0.06)^d$ 0.23	$p(\epsilon_2 > 0.28)$ 0.21	$p(\epsilon_3 > 0.47)$ 0.24
Reduced Form Sharing Rule vs. Nash Bargaining	$p(\epsilon_1 > 0.48)^e$ 8e-5	$p(\epsilon_2 > 0)$ 0.25	$p(\epsilon_3 > 0)$ 0.26

^a AOB model with $\epsilon_1 = \beta_1$, $\epsilon_2 = \beta_2 \gamma$ and $\epsilon_3 = \beta_3$ where $\beta_1, \beta_2, \beta_3$ are functions of δ and M , see section (2.5) in the text. Values of $\epsilon_1, \epsilon_2, \epsilon_3$ as implied by estimated parameters listed in Table 2.

^b Nash Bargaining model where ϵ_1 is a function of η , see section (2.6) in the text. Parameter value of ϵ_1 as implied by estimated parameters listed in Table 2.

^c Reduced form sharing rule model in which ϵ_1 and ϵ_3 are estimated as unrestricted parameters and ϵ_2 is set to obtain a steady state unemployment rate of 5.5 percent.

^d $p(\epsilon_1 > 0.06)$ denotes the probability that ϵ_1 in the estimated reduced form sharing rule model is larger than the mode value for ϵ_1 in the estimated AOB model.

^e $p(\epsilon_1 > 0.48)$ denotes the probability that ϵ_1 in the estimated reduced form sharing rule model is larger than the mode value for ϵ_1 in the estimated Nash model.

Table 5: Priors and Posteriors of Parameters: Simple and General Wage Rules

		Simple Wage Rule	General Wage Rule
	Prior Distribution \mathcal{D} , Mode , [2.5-97.5%]	Posterior Distribution Mode , [2.5-97.5%]	
<i>Price Setting Parameters</i>			
Price Stickiness, ξ	\mathcal{B} , 0.68 , [0.45 0.84]	0.75 , [0.70 0.85]	0.60 , [0.58 0.70]
Price Markup Parameter, λ	\mathcal{G} , 1.19 , [1.11 1.31]	1.36 , [1.26 1.47]	1.39 , [1.31 1.48]
<i>Monetary Authority Parameters</i>			
Taylor Rule: Smoothing, ρ_R	\mathcal{B} , 0.76 , [0.37 0.94]	0.87 , [0.84 0.89]	0.87 , [0.85 0.89]
Taylor Rule: Inflation, r_π	\mathcal{G} , 1.69 , [1.42 2.00]	1.33 , [1.23 1.68]	1.35 , [1.20 1.64]
Taylor Rule: GDP, r_y	\mathcal{G} , 0.08 , [0.03 0.22]	0.06 , [0.03 0.12]	0.05 , [0.02 0.10]
<i>Preferences and Technology Parameters</i>			
Consumption Habit, b	\mathcal{B} , 0.50 , [0.21 0.79]	0.82 , [0.80 0.85]	0.83 , [0.81 0.85]
Capacity Utilization Adjustment Cost, σ_a	\mathcal{G} , 0.32 , [0.09 1.23]	0.25 , [0.02 0.43]	0.28 , [0.13 0.40]
Investment Adjustment Cost, S''	\mathcal{G} , 7.50 , [4.57 12.4]	13.4 , [10.7 18.3]	14.8 , [10.7 17.8]
Capital Share, α	\mathcal{B} , 0.33 , [0.28 0.38]	0.23 , [0.20 0.27]	0.23 , [0.20 0.26]
Technology Diffusion, θ	\mathcal{B} , 0.50 , [0.13 0.87]	0.01 , [0.00 0.02]	0.01 , [0.00 0.02]
<i>Labor Market Parameters</i>			
Hiring Fixed Cost / Output, $100\eta_h$	\mathcal{G} , 0.91 , [0.50 1.67]	0.52 , [0.23 0.78]	0.47 , [0.25 0.86]
Vacancy Cost / Output, $100\eta_s$	\mathcal{G} , 0.05 , [0.01 0.28]	0.05 , [0.00 0.13]	0.03 , [0.00 0.14]
Matching Function Parameter, σ	\mathcal{B} , 0.50 , [0.31 0.69]	0.52 , [0.45 0.59]	0.55 , [0.47 0.60]
<i>Simple Wage Rule Parameters</i>			
Scaled Real Wage $_{t-1}$, ι_1	\mathcal{B} , 0.75 , [0.53 0.92]	0.96 , [0.92 0.97]	
Employment $_{t-1}$, ι_2	\mathcal{N} , 0.00 , [-1.96 1.96]	0.03 , [0.03 0.06]	
Neutral Technology Growth $_t$, ι_3	\mathcal{N} , 0.00 , [-1.96 1.96]	-0.15 , [-0.55 0.00]	
Investment Technology Growth $_t$, ι_4	\mathcal{N} , 0.00 , [-1.96 1.96]	-0.26 , [-0.53 -0.18]	
<i>General Wage Rule Parameters</i>			
Nominal Interest Rate $_{t-1}$, \varkappa_1	\mathcal{U} , n.a. , [-1.42 0.47]		-0.27 , [-0.39 0.07]
Scaled Capital $_{t-1}$, \varkappa_2	\mathcal{U} , n.a. , [-0.18 0.06]		0.06 , [0.02 0.06]
Employment $_{t-1}$, \varkappa_3	\mathcal{U} , n.a. , [-0.03 0.01]		-0.03 , [-0.04 0.01]
Price Dispersion $_{t-1}$, \varkappa_4	\mathcal{U} , n.a. , [-2.25 0.75]		-1.00 , [-2.04 0.77]
Composite Technology Diffusion $_{t-1}$, \varkappa_5	\mathcal{U} , n.a. , [-0.76 2.27]		0.01 , [0.01 0.24]
Scaled Consumption $_{t-1}$, \varkappa_6	\mathcal{U} , n.a. , [-0.13 0.40]		0.05 , [0.03 0.19]
Scaled Investment $_{t-1}$, \varkappa_7	\mathcal{U} , n.a. , [-0.08 0.24]		0.04 , [0.02 0.08]
Neutral Technology Growth $_t$, \varkappa_8	\mathcal{U} , n.a. , [-2.84 0.95]		-1.01 , [-1.75 -0.23]
Investment Technology Growth $_t$, \varkappa_9	\mathcal{U} , n.a. , [-0.67 0.22]		-0.29 , [-0.69 -0.04]
<i>Exogenous Processes Parameters</i>			
Standard Deviation Monetary Policy Shock, $400\sigma_R$	\mathcal{G} , 0.65 , [0.56 0.75]	0.58 , [0.51 0.64]	0.56 , [0.51 0.64]
Standard Deviation Neutral Technology Shk., $100\sigma_{\mu_z}$	\mathcal{G} , 0.08 , [0.03 0.22]	0.17 , [0.14 0.20]	0.17 , [0.14 0.20]
Standard Deviation Invest. Technology Shock, $100\sigma_\Psi$	\mathcal{G} , 0.08 , [0.03 0.22]	0.12 , [0.08 0.16]	0.12 , [0.09 0.16]
AR(1) Investment. Technology, ρ_Ψ	\mathcal{B} , 0.75 , [0.53 0.92]	0.70 , [0.60 0.83]	0.70 , [0.57 0.80]
<i>Memo Item</i>			
Log Marginal Likelihood (MCMC, 12 Observables):		306.5	308.9

Notes: For model specifications where particular parameter values are not relevant, the entries in this table are blank. Posterior mode and parameter distributions are based on a standard MCMC algorithm with a total of 10 million draws (11 chains, 50 percent of draws used for burn-in, draw acceptance rates about 0.24). \mathcal{B} , \mathcal{G} , \mathcal{N} and \mathcal{U} denote beta, gamma, normal and uniform distributions, respectively.

Figure 1: Responses to a Monetary Policy Shock: AOB vs. Calvo

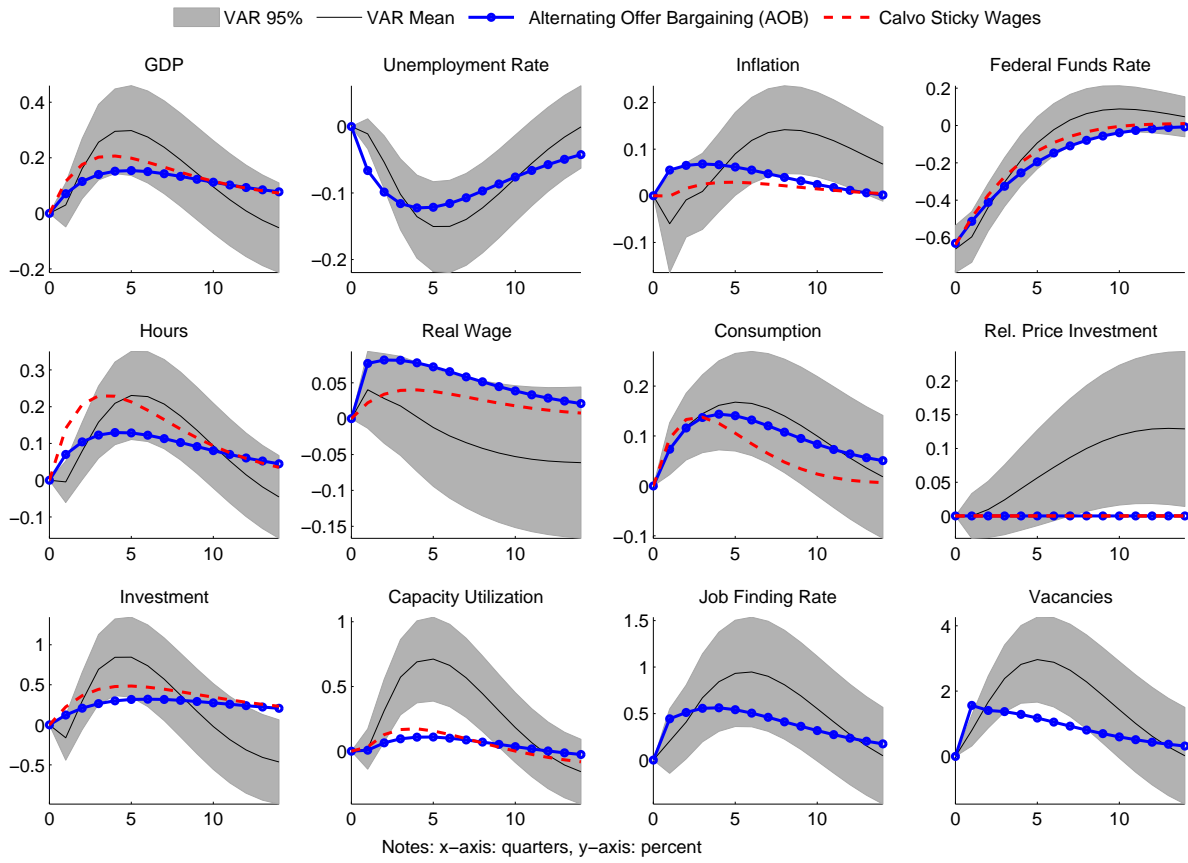


Figure 2: Responses to a Neutral Technology Shock: AOB vs. Calvo

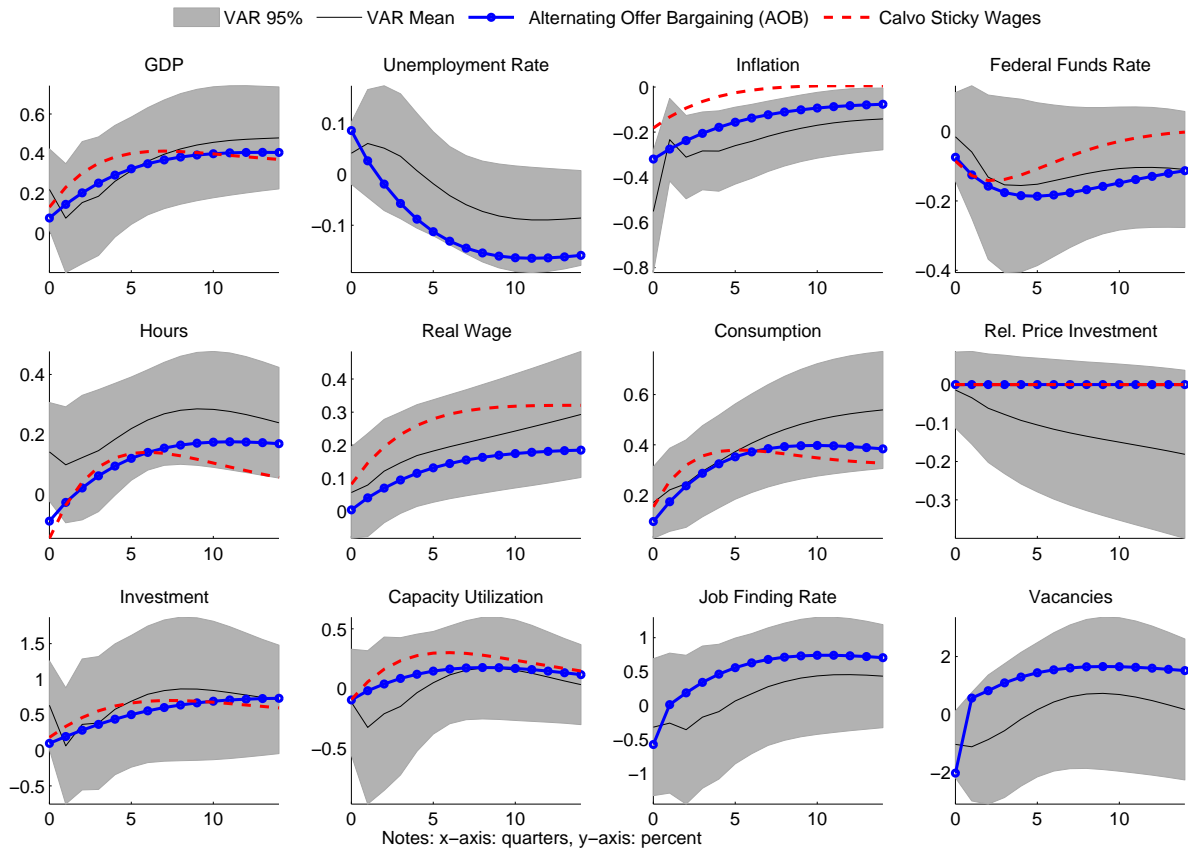


Figure 3: Responses to an Investment Specific Technology Shock: AOB vs. Calvo

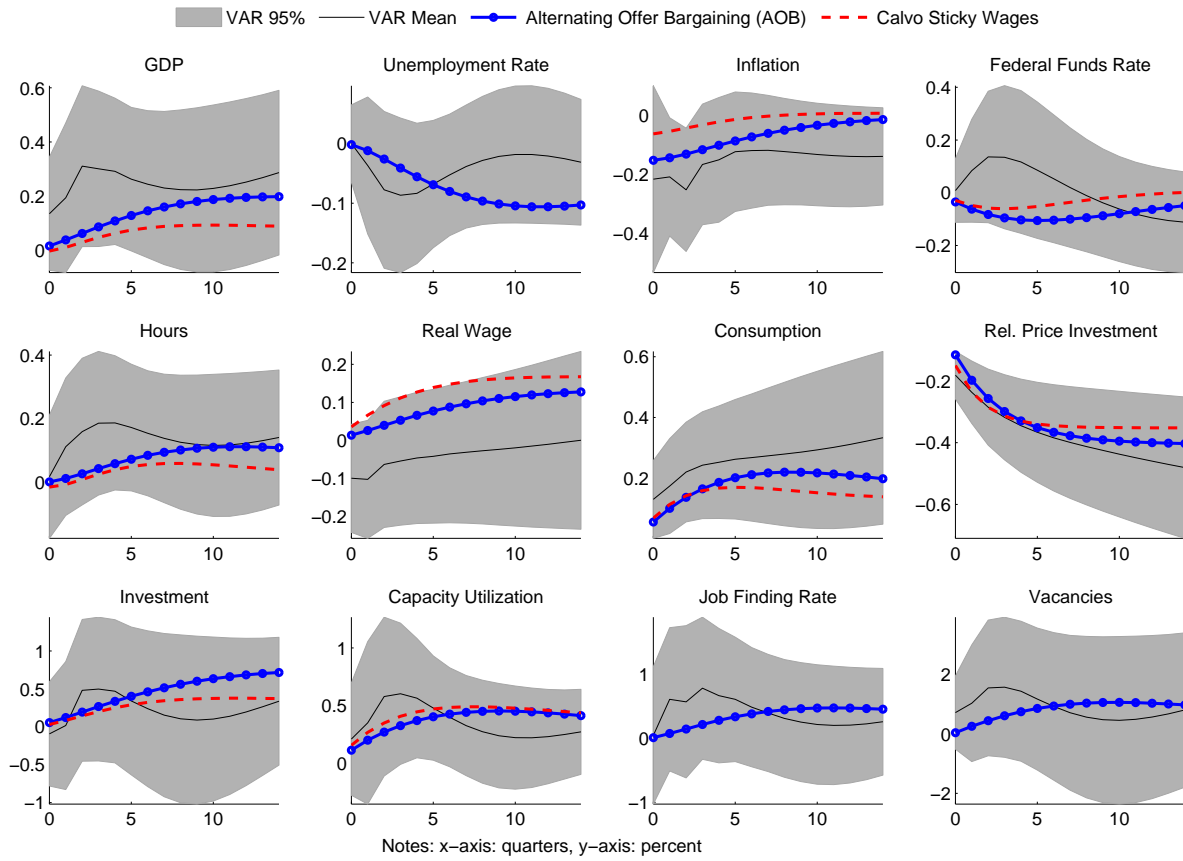


Figure 4: Responses to a Monetary Policy Shock: Nash Bargaining

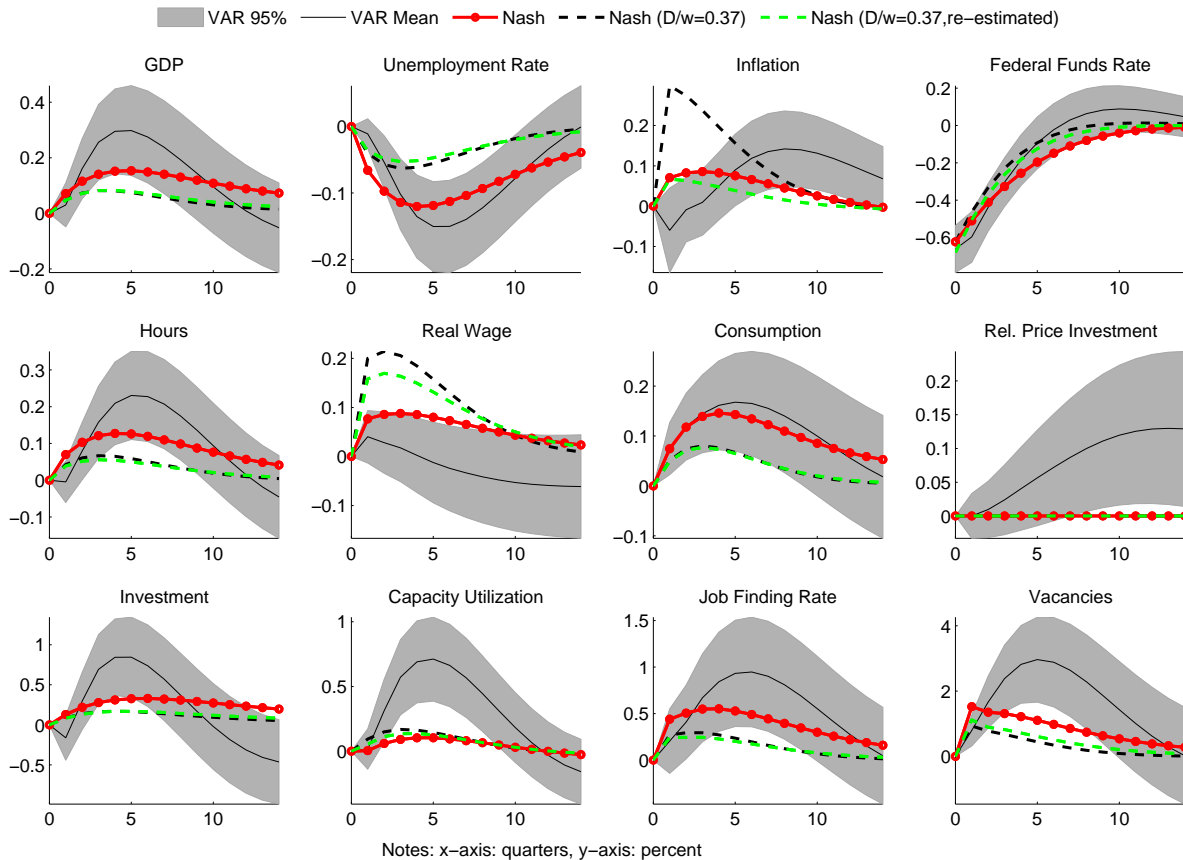


Figure 5: Responses to a Neutral Technology Shock: Nash Bargaining

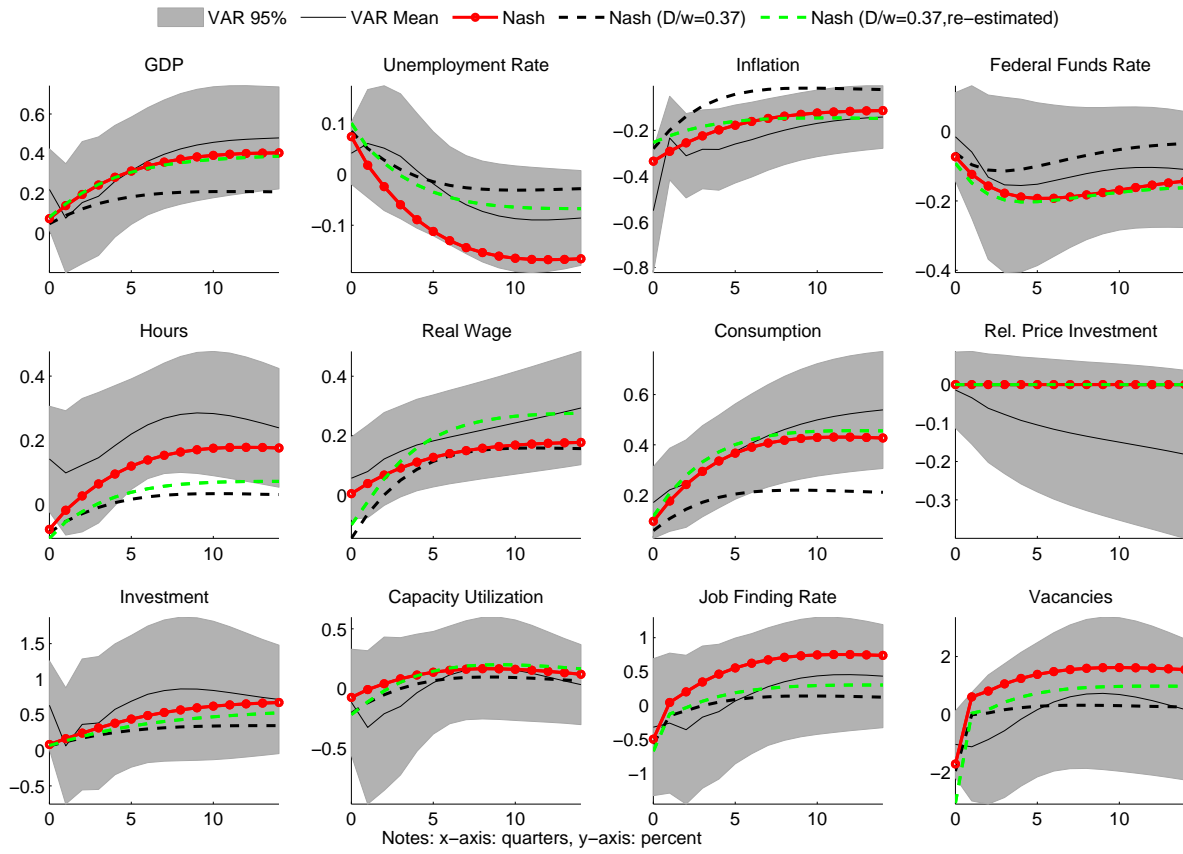


Figure 6: Responses to an Investment Specific Technology Shock: Nash Bargaining

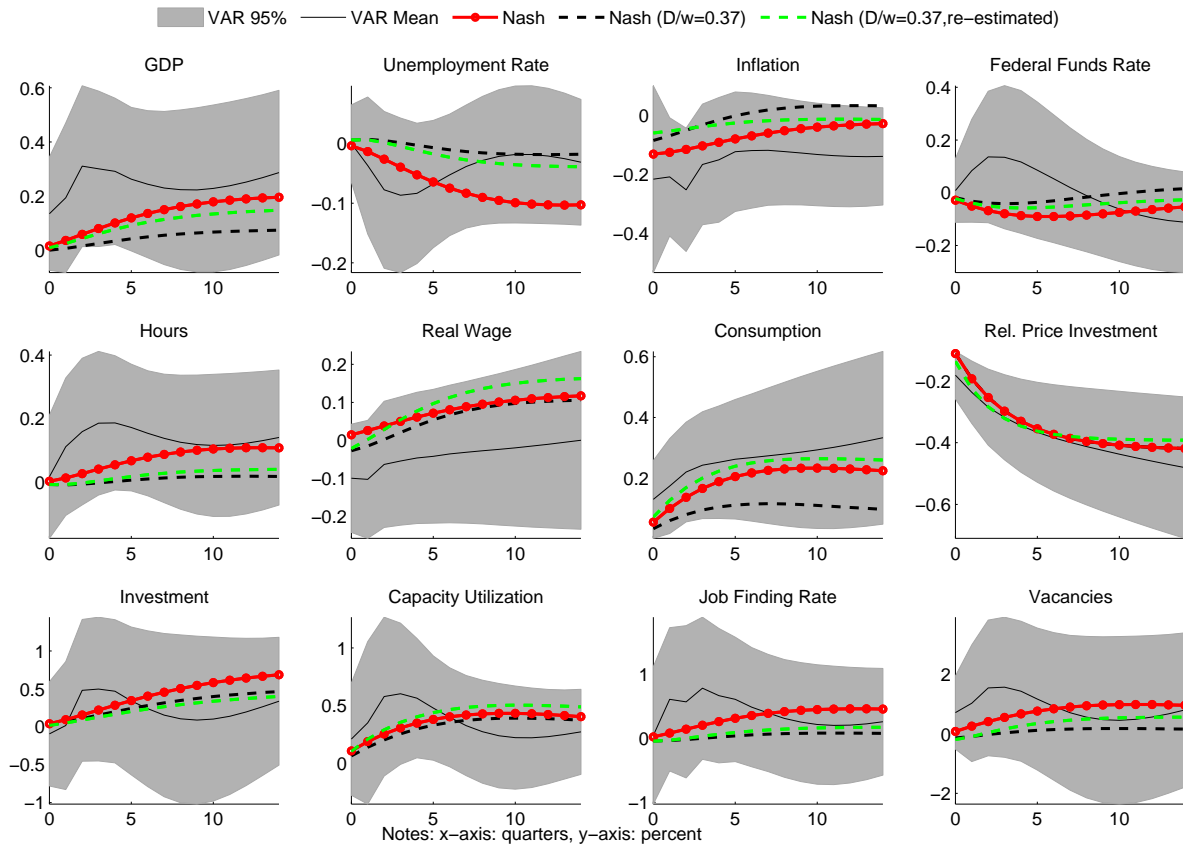
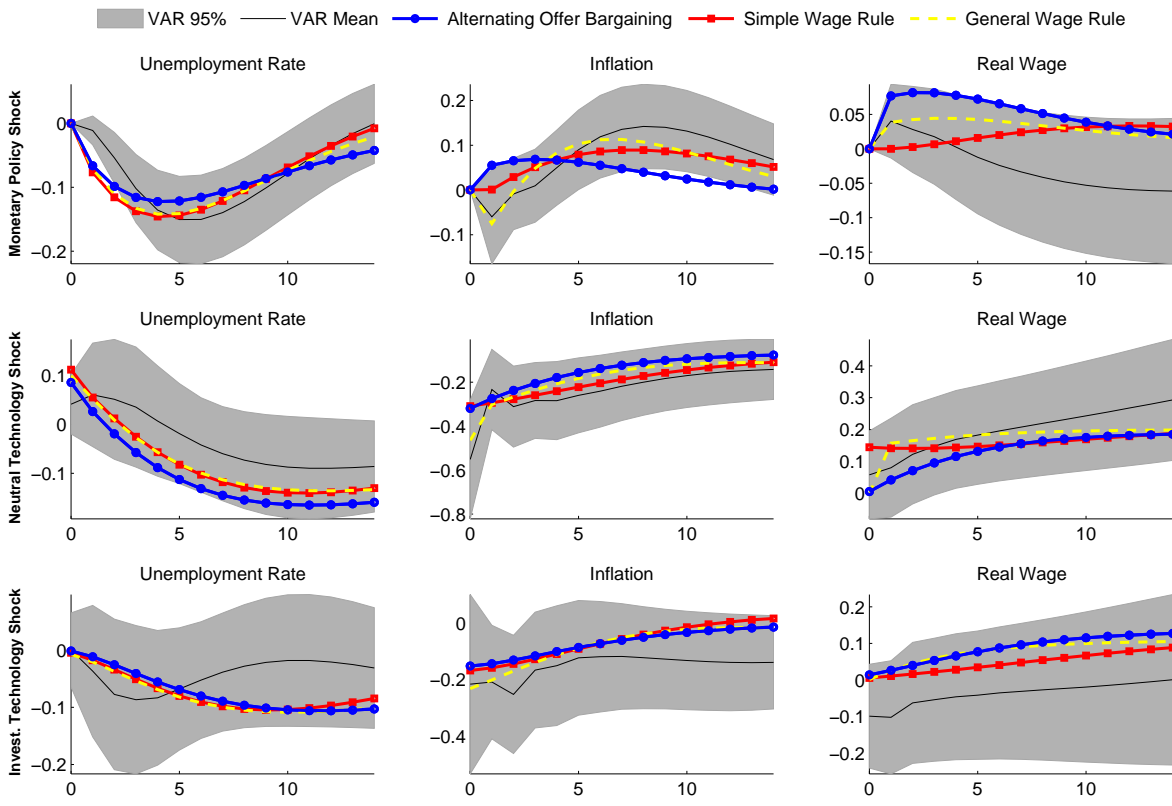
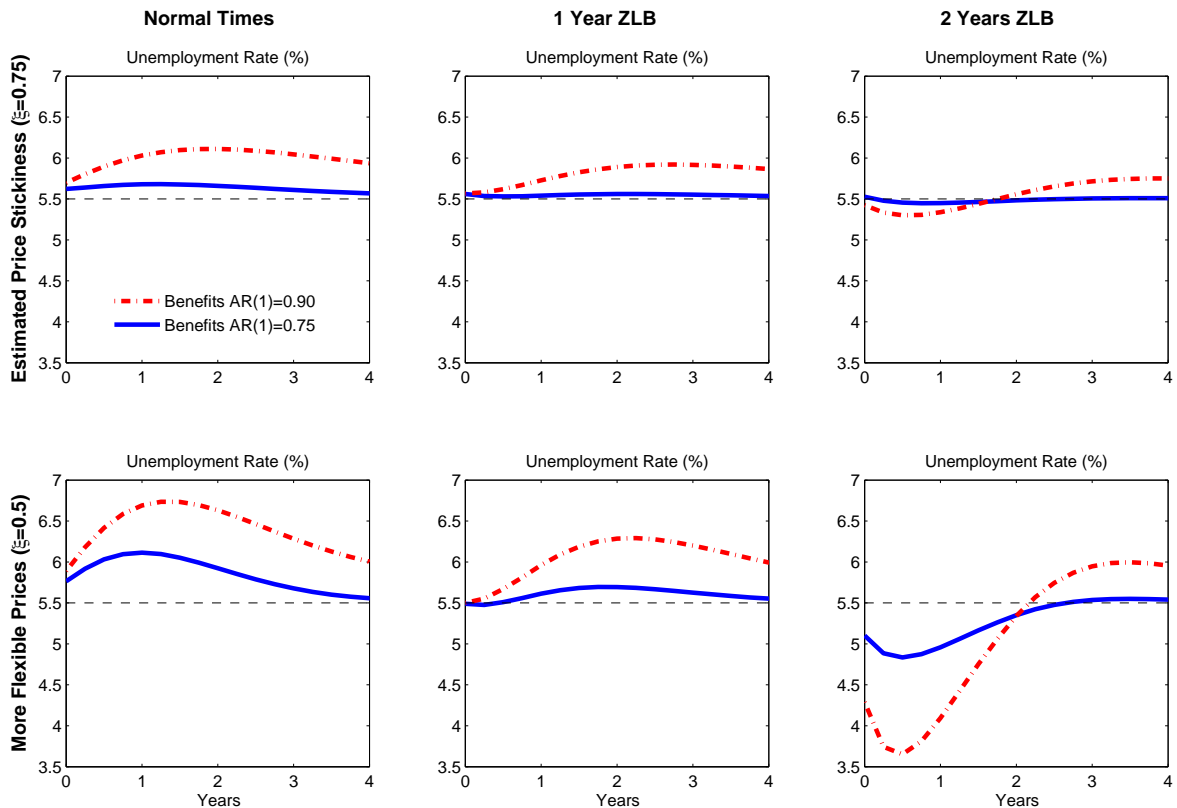


Figure 7: Impulse Responses to Shocks: Simple and General Wage Rules



Notes: x-axis: quarters, y-axis: percent

Figure 8: Dynamic Effects of a Rise in Unemployment Benefits



Notes: 1pp rise in unemployment benefits relative to steady state wage. Normal Times: Taylor rule. 1 or 2 Years ZLB: 1 or 2 years constant nominal interest rate.