State Dependency in Price and Wage Setting*

Shuhei Takahashi
Kyoto University

The frequency of nominal wage adjustments varies with macroeconomic conditions, but existing models exclude such state dependency in wage setting and assume constant frequency under time-dependent setting. This paper develops a New Keynesian model in which fixed wage-setting costs generate state-dependent wage setting. I find that state-dependent wage setting reduces the real impacts of monetary shocks compared with time-dependent setting. However, when parameterized to reproduce the fluctuations in wage rigidity in the United States, the state-dependent wage-setting model generates responses to monetary shocks similar to those of the time-dependent model. The trade-off between output gap and inflation variability is also similar between these two models.

JEL Codes: E31, E32.

*This paper is based on the third chapter of my dissertation submitted to the Ohio State University. I am grateful to Bill Dupor for his comments, encouragement, and guidance. I also would like to thank the editor (Pierpaolo Benigno), three anonymous referees, Michael Dotsey, Paul Evans, Yuko Imura, Aubhik Khan, Robert King, Oleksiy Kryvtsov, Nan Li, Virgiliu Midrigan, Tomoyuki Nakajima, Masao Ogaki, Ricardo Reis, Jose-Victor Rios-Rull, Takeki Sunakawa, Tamon Takamura, Julia Thomas, Alexander Wolman, and seminar and conference participants at the Macro Lunch Workshop at the Ohio State University, DSGE Workshop at Senshu, Macroeconomics Workshop at Kyoto, Bank of Canada, Eastern Economic Association Annual Conference 2011, Midwest Economics Association Annual Meeting 2011, Summer Workshop on Economic Theory 2014, European Meeting of the Econometric Society 2014, and Fall 2014 Midwest Macro Meeting for valuable comments and suggestions. I thank the Kyoto University Foundation and Zengin Foundation for financial support. Any remaining errors are my own. Author contact: Institute of Economic Research, Kyoto University, Yoshida-Honmachi, Sakyo-ku, Kyoto 606-8501, Japan. Tel:+81-75-753-7153; E-mail: takahashi@kier.kyoto-u.ac.jp.

1. Introduction

The transmission of monetary disturbances has been an important issue in macroeconomics. Recent studies, such as Huang and Liu (2002) and Christiano, Eichenbaum, and Evans (2005), show that nominal wage stickiness is one of the key factors in generating persistent responses of output and inflation to monetary shocks in New Keynesian models. However, existing studies establish the importance of sticky wages under Calvo (1983)-style or Taylor (1980)-style setting. Such time-dependent setting models are extreme in that because of the exogenous timing and constant frequency of wage setting, wage adjustments occur only through changes in the intensive margin. In contrast, there is some evidence that the extensive margin also matters, i.e., evidence for state dependency in wage setting. For example, reviewing empirical studies on micro-level wage adjustments, Taylor (1999) concludes that "the frequency of wage setting increases with the average rate of inflation." Further, according to Daly, Hobijn, and Lucking (2012) and Daly and Hobijn (2014), the fraction of wages not changed for a year rises in recessions in the United States.[1] How does the impact of monetary shocks differ under state-dependent and time-dependent wage setting? Does state dependency in wage setting significantly affect the monetary transmission and the trade-off between output and inflation variability in the U.S. economy?

To answer these questions, the present paper constructs a New Keynesian model with state-dependent price and wage setting, building on the seminal state-dependent pricing model of Dotsey, King, and Wolman (1999).[2] The price-setting side of the model is essentially the same as that of Dotsey, King, and Wolman (1999). Firms change their price in a staggered manner because fixed costs for price

[1]In addition to these empirical supports, state-dependent wage-setting models are theoretically attractive for policy analysis because the timing and frequency of wage adjustments could change with policy.

[2]The framework of Dotsey, King, and Wolman (1999) is widely used for analyzing aggregate price dynamics. Bakhshi, Kahn, and Rudolf (2007) derive the New Keynesian Phillips curve for the model. Landry (2009, 2010) develops a two-country model with state-dependent pricing and analyzes exchange rate movements. Dotsey and King (2005, 2006) analyze the impact of various real-side features on the monetary transmission. Nakov and Thomas (2014) analyze optimal monetary policy.

adjustments differ across firms. However, since all firms face the identical sequence of marginal costs and price-setting costs are independently distributed over time, adjusting firms set the same price as in typical time-dependent pricing models, making the price distribution tractable. In contrast, the wage-setting side of the present model departs from the flexible-wage setting of Dotsey, King, and Wolman (1999). Specifically, as in Blanchard and Kiyotaki (1987) and Erceg, Henderson, and Levin (2000), households supply a differentiated labor service and set the wage for their labor. Further, I introduce fixed wage-setting costs that differ across households and evolve independently over time.[3] Hence, households adjust their wage in a staggered way. Since adjusting households set the same wage under assumptions commonly made for time-dependent setting, the wage distribution is also tractable. Therefore, the present model with state dependency in both price and wage setting can be solved with the method developed by Dotsey, King, and Wolman (1999).

The present paper finds that compared with the time-dependent counterpart, the state-dependent wage-setting model shows a smaller real impact of monetary shocks.[4] Further, these two wage-setting regimes could imply opposite relationships between monetary non-neutralities and the elasticity of demand for differentiated labor services, which is a key parameter for wage setting. Specifically, non-neutralities could decrease with the elasticity under state-dependent wage setting, while as shown by Huang and Liu (2002), non-neutralities increase under time-dependent setting.

To understand the impact of state dependency in wage setting described above, consider an expansionary monetary shock. In the presence of nominal rigidity, the aggregate price, consumption, and labor hours all increase, lowering real wages and raising the marginal rate of substitution of leisure for consumption. Because the timing of wage adjustments is endogenous, the fraction of households raising their wage increases under state-dependent setting. In contrast, the

[3]Blanchard and Kiyotaki (1987) also assume fixed wage-setting costs. In contrast, Kim and Ruge-Murcia (2009) introduce convex wage-adjustment costs.

[4]Following the convention of the state-dependent pricing literature, the timing and frequency of wage adjustments under time-dependent setting are fixed to those at the steady state of the state-dependent wage-setting model and hence they are invariant to shocks.

fraction remains unchanged under time-dependent setting. Further, the resetting wage, which is common to all adjusting households, rises more quickly under state-dependent setting than under time-dependent setting. The key to this result is that under monopolistic competition, the demand for households' labor hours increases as the aggregate wage rises relative to their wage. This implies that since more households raise their wage, adjusting households find it optimal to raise their wage more substantially under state-dependent setting than under time-dependent setting. In response, firms raise their price more quickly. Hence, state-dependent wage setting facilitates nominal adjustments following monetary disturbances and reduces non-neutralities compared with time-dependent setting.[5]

The relative wage concern also governs the relationship between monetary non-neutralities and the elasticity of demand for differentiated labor. Under a higher elasticity, households' labor hours decrease more elastically as their wage rises relative to the aggregate wage. Hence, when wage setting is time dependent, adjusting households raise their wage less substantially under a higher elasticity. Since the fraction of adjusting households is unchanged, monetary non-neutralities increase with the elasticity under time-dependent wage setting, as shown by Huang and Liu (2002). This relationship could be overturned under state-dependent setting. Under a higher elasticity, labor hours of non-adjusting households increase more substantially and therefore more households raise their wage. If this effect is strong enough, adjusting households also set a higher wage when the elasticity is higher. As a result, under state-dependent setting, nominal wage adjustments could occur more quickly and monetary non-neutralities could become smaller when the elasticity increases.

Next, the present paper quantifies the impact of state dependency in wage setting on the transmission of monetary shocks and the trade-off between the output gap and inflation stability for the

[5]Since adjustment decisions are endogenous under state-dependent setting, adjusting households could shift to those who raise their wage substantially. In the present model, those who conduct a large wage increase are those who fixed their wage for a long period of time. Such a selection effect is weak in the present model and, as shown later, it is consistent with data.

U.S. economy. For this purpose, I augment my model with capital accumulation, capital adjustment costs, habit formation, and variable capital utilization because as shown by Christiano, Eichenbaum, and Evans (2005) and Smets and Wouters (2007), these real-side features play a crucial role in the monetary transmission of a New Keynesian model. Further, several real shocks are introduced in order to generate a trade-off between stabilizing the output gap and inflation. I then choose the distribution of wage-setting costs so that the model reproduces the fluctuations in the fraction of wages not changed for a year, specifically the variation in the "wage rigidity meter" released by the Federal Reserve Bank of San Francisco.[6]

I find that the distribution of wage-setting costs is similar to the Calvo-type distribution. More specifically, in any given period, most households draw costs close to zero or the maximum, implying small fluctuations in the extensive margin. As a result, the state-dependent wage-setting model shows a response to monetary shocks quite similar to that of the time-dependent counterpart. For example, the cumulative response of output decreases only by about 10 percent when wage setting switches from time to state dependency. The trade-off between the stability of the output gap and the stability of inflation is also similar between the two models, and the optimal interest rate monetary policy rule under time-dependent wage setting performs well under state-dependent wage setting. The results indicate that the time-dependent wage-setting model is a good approximation to the state-dependent wage-setting model considered here and calibrated to the variation in wage rigidity in the United States, at least for analyzing the monetary transmission and the optimal interest rate rule.

This paper is related to the literature that studies how various features of wage setting influence the transmission of monetary shocks. Olivei and Tenreyro (2007, 2010) show that the seasonality in the output response to a monetary shock can be explained by the seasonality in the frequency of wage changes. Dixon and Le Bihan (2012) show that considering the heterogeneity in wage spells

[6]Such long-term rigid wages are key to generating the persistent response to monetary shocks in New Keynesian models (Dixon and Kara 2010). Further, as discussed in footnote 5, the selection effect in the present model mainly works through changes in the fraction of those long-term rigid wages.

observed in micro-level data helps account for the persistent response of output and inflation to a monetary shock. Although these studies analyze important patterns of wage setting, their models assume time-dependent wage setting. The present paper contributes to the literature by examining state dependency in wage setting, which is another feature of wage adjustments.

This paper is also related to the literature on state-dependent price setting. Following Caplin and Spulber (1987) and Caplin and Leahy (1991), more recent contributions analyze how state-dependent pricing influences the monetary transmission in a dynamic stochastic general equilibrium model. Examples include Dotsey, King, and Wolman (1999), Dotsey and King (2005, 2006), Klenow and Kryvtsov (2005, 2008), Devereux and Siu (2007), Golosov and Lucas (2007), Gertler and Leahy (2008), Nakamura and Steinsson (2010), Costain and Nakov (2011a, 2011b), and Midrigan (2011). While these studies describe price setting in a rich way, they assume flexible wages. The contribution of the present paper is to construct a full-blown model with state-dependent price and wage setting, which is comparable to the state-of-the-art models with time-dependent price and wage setting developed by Christiano, Eichenbaum, and Evans (2005) and Smets and Wouters (2007).

The rest of the present paper is organized as follows. Section 2 describes the benchmark model with state-dependent price and wage setting, and section 3 determines the parameter values. Section 4 uses the benchmark model to show how state dependency in wage setting influences the transmission of monetary disturbances. Section 5 develops the full model with various real-side features and shocks in order to evaluate the importance of state dependency in wage setting to the monetary transmission and the trade-off between output and inflation stability for the U.S. economy. Section 6 concludes.

2. Benchmark Model

This section introduces state dependency in price and wage setting into a simple New Keynesian model. To this end, I assume fixed costs for price and wage changes and make the timing of price and wage adjustments endogenous.

2.1 Firms

There is a continuum of firms of measure one.[7] Each firm produces a differentiated good indexed by $z \in [0,1]$. The production function is

$$y_t(z) = k_t(z)^{1-\alpha} n_t(z)^{\alpha}, \tag{1}$$

where $\alpha \in [0,1], y_t(z)$ is output, $k_t(z)$ is capital, and $n_t(z)$ is the composite labor, which is defined below. As in Dotsey, King, and Wolman (1999) and Erceg, Henderson, and Levin (2000), households own capital, and the total amount of capital is fixed.[8] Firms rent capital and the composite labor in competitive markets. Cost minimization implies the following first-order conditions:

$$\alpha mc_t \left[\frac{k_t(z)}{n_t(z)}\right]^{1-\alpha} = w_t \tag{2}$$

and

$$(1-\alpha) mc_t \left[\frac{k_t(z)}{n_t(z)}\right]^{-\alpha} = q_t, \tag{3}$$

where mc_t is the real marginal cost, w_t is the real wage for the composite labor, and q_t is the real rental rate of capital.

Each firm sets the price of its product $P_t(z)$, and the demand for each product $c_t(z)$ is given by

$$c_t(z) = \left[\frac{P_t(z)}{P_t}\right]^{-\epsilon^p} c_t, \tag{4}$$

where $\epsilon^p > 1$ and P_t is the aggregate price index, which is defined as

$$P_t = \left[\int_0^1 P_t(z)^{1-\epsilon^p} dz\right]^{\frac{1}{1-\epsilon^p}}, \tag{5}$$

[7]This subsection closely follows the explanation by Dotsey, King, and Wolman (1999).

[8]The full model in section 5 introduces aggregate total factor productivity (TFP) shocks, capital accumulation, and variable capital utilization. I also solved the model with no capital ($\alpha = 1$) and found no significant change relative to the results of the benchmark model.

and c_t is the demand for the composite good. The composite good is defined by

$$c_t = \left[\int_0^1 c_t(z)^{\frac{\epsilon^p - 1}{\epsilon^p}} dz \right]^{\frac{\epsilon^p}{\epsilon^p - 1}}. \tag{6}$$

Firms produce the quantity demanded: $y_t(z) = c_t(z)$.

Firms change their price infrequently because price adjustments incur fixed costs. Specifically, in each period, each firm draws a fixed price-setting cost $\xi_t^p(z)$, denominated in the composite labor, from a continuous distribution $G^p(\xi^p)$. These costs are independently and identically distributed across time and firms. Since firms face the identical marginal cost of production, the resetting price P_t^* is common to all adjusting firms, as under typical time-dependent price setting. Consequently, at the beginning of any given period before drawing current price-setting costs, firms are distinguished only by the last price adjustment and a fraction $\theta_{j,t}^p$ of firms charge $P_{t-j}^*, j = 1, \ldots, J$. The price distribution, including the number of price vintages J, is endogenously determined. Since inflation is positive and price-setting costs are bounded, firms eventually change their price and J is finite.

Let $v_{0,t}^p$ denote the real value of a firm that resets its price in the current period and $v_{j,t}^p, j = 1, \ldots, J-1$ denote the real value of a firm that keeps its price unchanged at P_{t-j}^*. No firm keeps its price at P_{t-J}^*. Each firm changes its price if

$$v_{0,t}^p - v_{j,t}^p \geq w_t \xi_t^p(z). \tag{7}$$

The left-hand side is the benefit of changing the price, while the right-hand side is the cost. For each price vintage, the fraction of firms that change their price is given by

$$\alpha_{j,t}^p = G^p \left(\frac{v_{0,t}^p - v_{j,t}^p}{w_t} \right), \tag{8}$$

$j = 1, \ldots, J-1$, and $\alpha_{J,t}^p = 1$. This is also the probability of price adjustments before firms draw their current price-setting cost. The fraction and probability of price changes increase as the benefit of price adjustments increases.

The value of a firm that adjusts its price is

$$v^p_{0,t} = \max_{P^*_t} \left\{ \left(\frac{P^*_t}{P_t} - mc_t \right) \left(\frac{P^*_t}{P_t} \right)^{-\epsilon^p} c_t \right. \tag{9}$$
$$\left. + \beta E_t \frac{\lambda_{t+1}}{\lambda_t} [(1 - \alpha^p_{1,t+1}) v^p_{1,t+1} + \alpha^p_{1,t+1} v^p_{0,t+1} - w_{t+1} \Xi^p_{1,t+1}] \right\},$$

where E_t is the conditional expectation and λ_t is households' marginal utility of consumption. The first line is the current profit. The second line is the present value of the expected profit. With probability $(1 - \alpha^p_{1,t+1})$, the firm keeps P^*_t in the next period. With probability $\alpha^p_{1,t+1}$, the firm resets its price again in the next period. The last term is the expected next-period price-setting cost, and $\Xi^p_{j,t+1}, j = 1, \ldots, J$ is defined by

$$\Xi^p_{j,t+1} = \int_0^{\bar{\xi}^p_{j,t+1}} x g^p(x) dx, \tag{10}$$

where g^p denotes the probability density function of price-setting costs. Note that $\bar{\xi}^p_{J,t+1} = B^p$, where B^p is the maximum cost.

The value of a firm that keeps its price is

$$v^p_{j,t} = \left(\frac{P^*_{t-j}}{P_t} - mc_t \right) \left(\frac{P^*_{t-j}}{P_t} \right)^{-\epsilon^p} c_t + \beta E_t \frac{\lambda_{t+1}}{\lambda_t}$$
$$\times \left[(1 - \alpha^p_{j+1,t+1}) v^p_{j+1,t+1} + \alpha^p_{j+1,t+1} v^p_{0,t+1} - w_{t+1} \Xi^p_{j+1,t+1} \right], \tag{11}$$

$j = 1, \ldots, J-2$, and

$$v^p_{J-1,t} = \left(\frac{P^*_{t-(J-1)}}{P_t} - mc_t \right) \left(\frac{P^*_{t-(J-1)}}{P_t} \right)^{-\epsilon^p} c_t$$
$$+ \beta E_t \frac{\lambda_{t+1}}{\lambda_t} [v^p_{0,t+1} - w_{t+1} \Xi^p_{J,t+1}]. \tag{12}$$

The optimal resetting price P^*_t satisfies the first-order condition for (9):

$$\left(\frac{P^*_t}{P_t} \right)^{-\epsilon^p} \frac{c_t}{P_t} - \epsilon^p \left(\frac{P^*_t}{P_t} - mc_t \right) \left(\frac{P^*_t}{P_t} \right)^{-\epsilon^p - 1} \frac{c_t}{P_t}$$
$$+ \beta E_t \frac{\lambda_{t+1}}{\lambda_t} (1 - \alpha^p_{1,t+1}) \frac{\partial v^p_{1,t+1}}{\partial P^*_t} = 0. \tag{13}$$

Replacing the terms $\partial v^p_{j,t+j}/\partial P^*_t, j = 1, \ldots, J-1$ with (11) and (12) yields

$$P^*_t = \frac{\epsilon^p}{\epsilon^p - 1} \frac{E_t \sum_{j=0}^{J-1} \beta^j \left(\frac{\omega^p_{j,t+j}}{\omega^p_{0,t}}\right) \left(\frac{\lambda_{t+j}}{\lambda_t}\right) P^{\epsilon^p - 1}_{t+j} c_{t+j} P_{t+j} mc_{t+j}}{E_t \sum_{j=0}^{J-1} \beta^j \left(\frac{\omega^p_{j,t+j}}{\omega^p_{0,t}}\right) \left(\frac{\lambda_{t+j}}{\lambda_t}\right) P^{\epsilon^p - 1}_{t+j} c_{t+j}}, \tag{14}$$

where $\omega^p_{j,t+j}/\omega^p_{0,t} = (1-\alpha^p_{j,t+j})(1-\alpha^p_{j-1,t+j-1}) \cdots (1-\alpha^p_{1,t+1}), j = 1, \ldots, J-1$ is the probability of keeping P^*_t until $t+j$. The probability is invariant over time under time-dependent setting. In the present model, in contrast, the probability endogenously evolves, reflecting state dependency in price setting (see (8)). However, as in typical time-dependent price-setting models, the optimal price is a constant markup times the weighted average of the current and expected future nominal marginal costs $(P_{t+j} mc_{t+j})$.

2.2 Households

There is a continuum of households of measure one. Each household supplies a differentiated labor service, which is indexed by $h \in [0,1]$. A household's preferences are represented by

$$E_t \sum_{l=0}^{\infty} \beta^l [\ln c_{t+l}(h) - \chi n_{t+l}(h)^{\zeta}], \tag{15}$$

where $\beta \in (0,1), \chi > 0, \zeta \geq 1$, $c_t(h)$ is consumption of the composite good, and $n_t(h)$ is hours worked.

Each household sets the wage rate for its labor service $W_t(h)$ and supplies labor hours demanded $n_t(h)$. As in Erceg, Henderson, and Levin (2000), a representative labor aggregator combines households' labor services, and all firms hire the composite labor from the aggregator. The composite labor is defined as

$$n_t = \left[\int_0^1 n_t(h)^{\frac{\epsilon^w - 1}{\epsilon^w}} dh\right]^{\frac{\epsilon^w}{\epsilon^w - 1}}, \tag{16}$$

where $\epsilon^w > 1$. Cost minimization by the labor aggregator implies the demand for each labor service:

$$n_t(h) = \left[\frac{W_t(h)}{W_t}\right]^{-\epsilon^w} n_t, \tag{17}$$

where W_t is the aggregate wage index, which is defined as

$$W_t = \left[\int_0^1 W_t(h)^{1-\epsilon^w} dh\right]^{\frac{1}{1-\epsilon^w}}. \tag{18}$$

Households infrequently adjust their wage because wage setting incurs fixed costs. Similar to price setting, in each period, each household draws a fixed wage-setting cost $\xi_t^w(h)$, denominated in the composite labor, from a continuous distribution $G^w(\xi^w)$. These costs are independently and identically distributed over time and across households.

As in typical New Keynesian models, there exists a complete set of nominal contingent bonds, implying that a household faces the budget constraint

$$\begin{aligned} q_t k_t(h) + \frac{W_t(h)n_t(h)}{P_t} + \frac{M_{t-1}(h)}{P_t} + \frac{B_{t-1}(h)}{P_t} + \frac{D_t(h)}{P_t} \\ = c_t(h) + \frac{\delta_{t+1,t}B_t(h)}{P_t} + \frac{M_t(h)}{P_t} + w_t\xi_t^w(h)I_t(h), \end{aligned} \tag{19}$$

where $k_t(h)$ is capital holding, $M_t(h)$ is money holding, $B_{t-1}(h)$ is the quantity of the contingent bond given the current state of nature, $D_t(h)$ is nominal profits paid by firms, $\delta_{t+1,t}$ is the vector of the prices of contingent bonds, $B_t(h)$ is the vector of those bonds purchased, and $I_t(h)$ is the indicator function that takes one if households reset their wage in the period and zero otherwise. Assuming that households have identical initial wealth and the utility function is separable between consumption and leisure, households have identical consumption as a result of perfect insurance: $\lambda_t(h) = \lambda_t$.[9]

[9] As in Khan and Thomas (2014), I assume nominal bonds contingent on both aggregate and idiosyncratic shocks. Another setting that leads to perfect insurance for consumption is a representative household with a large number of workers, as in Huang, Liu, and Phaneuf (2004). Relaxing the assumption of perfect consumption insurance requires keeping track of the joint distribution of wages and wealth across households. I leave it to future research.

The existence of perfect insurance for consumption implies that the optimal wage W_t^* is common to all adjusting households, as under standard time-dependent setting. Accordingly, at the start of any given period, a fraction $\theta_{q,t}^w$ of households charge $W_{t-q}^*, q = 1, \ldots, Q$. The wage distribution, including the number of wage vintages Q, is endogenously determined. Under positive inflation and bounded wage-setting costs, households eventually change their wage and Q is finite.

Let $v_{0,t}^w$ denote the utility of a household (relating to wage-setting decisions) that resets its wage in the current period and $v_{q,t}^w, q = 1, \ldots, Q-1$ denote the utility of a household that keeps its wage unchanged at W_{t-q}^*. No household keeps its wage at W_{t-Q}^*. Each household changes its wage if

$$v_{0,t}^w - v_{q,t}^w \geq w_t \lambda_t \xi_t^w(h). \tag{20}$$

The left-hand side is the benefit of changing the wage, while the right-hand side is the cost. For each wage vintage, the fraction of adjusting households is given by

$$\alpha_{q,t}^w = G^w \left(\frac{v_{0,t}^w - v_{q,t}^w}{w_t \lambda_t} \right), \tag{21}$$

$q = 1, \ldots, Q-1$, and $\alpha_{Q,t}^w = 1$. This is also the probability of wage adjustments before households draw their current wage-setting cost. The fraction and probability of wage changes increase with the value of adjusting wages.

The utility of a household adjusting its wage is

$$v_{0,t}^w = \max_{W_t^*} \left\{ \lambda_t \frac{W_t^*}{P_t} \left(\frac{W_t^*}{W_t} \right)^{-\epsilon^w} n_t - \chi \left[\left(\frac{W_t^*}{W_t} \right)^{-\epsilon^w} n_t \right]^\zeta \right.$$
$$\left. + \beta E_t[(1 - \alpha_{1,t+1}^w) v_{1,t+1}^w + \alpha_{1,t+1}^w v_{0,t+1}^w - \lambda_{t+1} w_{t+1} \Xi_{1,t+1}^w] \right\}. \tag{22}$$

The first line is the current utility. The second line is the present value of the expected utility. With probability $(1 - \alpha_{1,t+1}^w)$, the household keeps W_t^* in the next period. With probability $\alpha_{1,t+1}^w$, the household resets its wage again in the next period. The last term is the present value of the expected next-period wage-setting cost, and $\Xi^w_{q,t+1}, q = 1, \ldots, Q$ is defined by

$$\Xi^w_{q,t+1} = \int_0^{\bar{\xi}^w_{q,t+1}} x g^w(x) dx, \tag{23}$$

where g^w denotes the probability density function of wage-setting costs. Note that $\bar{\xi}^w_{Q,t+1} = B^w$, where B^w is the maximum cost.

The utility of a non-adjusting household is

$$\begin{aligned} v^w_{q,t} = {} & \lambda_t \frac{W^*_{t-q}}{P_t} \left(\frac{W^*_{t-q}}{W_t} \right)^{-\epsilon^w} n_t - \chi \left[\left(\frac{W^*_{t-q}}{W_t} \right)^{-\epsilon^w} n_t \right]^{\zeta} \\ & + \beta E_t [(1 - \alpha^w_{q+1,t+1}) v^w_{q+1,t+1} + \alpha^w_{q+1,t+1} v^w_{0,t+1} \\ & - \lambda_{t+1} w_{t+1} \Xi^w_{q+1,t+1}], \end{aligned} \tag{24}$$

$q = 1, \ldots, Q-2$, and

$$\begin{aligned} & v^w_{Q-1,t} \\ & = \lambda_t \frac{W^*_{t-(Q-1)}}{P_t} \left(\frac{W^*_{t-(Q-1)}}{W_t} \right)^{-\epsilon^w} n_t - \chi \left[\left(\frac{W^*_{t-(Q-1)}}{W_t} \right)^{-\epsilon^w} n_t \right]^{\zeta} \\ & + \beta E_t [v^w_{0,t+1} - \lambda_{t+1} w_{t+1} \Xi^w_{Q,t+1}]. \end{aligned} \tag{25}$$

The optimal wage W^*_t satisfies the first-order condition for (22):

$$\begin{aligned} & \frac{\lambda_t}{P_t} \left(\frac{W^*_t}{W_t} \right)^{-\epsilon^w} n_t - \epsilon^w \lambda_t \frac{W^*_t}{P_t} \left(\frac{W^*_t}{W_t} \right)^{-\epsilon^w - 1} \frac{n_t}{W_t} \\ & + \epsilon^w \chi \zeta \left(\frac{W^*_t}{W_t} \right)^{-\epsilon^w \zeta - 1} \frac{n_t^{\zeta}}{W_t} \\ & + \beta E_t (1 - \alpha^w_{1,t+1}) \frac{\partial v^w_{1,t+1}}{\partial W^*_t} = 0. \end{aligned} \tag{26}$$

Replacing the terms $\partial v^w_{q,t+q}/\partial W^*_t$, $q = 1, \ldots, Q-1$ with (24) and (25) implies that

$$E_t \sum_{q=0}^{Q-1} \beta^q \left(\frac{\omega^w_{q,t+q}}{\omega^w_{0,t}} \right) \times \left\{ \frac{\epsilon^w - 1}{\epsilon^w} \frac{W^*_t}{P_{t+q}} \lambda_{t+q} - \chi\zeta \left[\left(\frac{W^*_t}{W_{t+q}} \right)^{-\epsilon^w} n_{t+q} \right]^{\zeta-1} \right\} \times \left(\frac{W^*_t}{W_{t+q}} \right)^{-\epsilon^w} n_{t+q} = 0, \tag{27}$$

where $\omega^w_{q,t+q}/\omega^w_{0,t} = (1-\alpha^w_{q,t+q})(1-\alpha^w_{q-1,t+q+1})...(1-\alpha^w_{1,t+1}), q = 1, \ldots, Q-1$ denotes the probability of keeping W^*_t until $t+q$. Because of state dependency in wage setting, the probability endogenously varies over time, as indicated by (21). However, as under time-dependent setting, households set the wage equating the discounted expected marginal utility of labor income with the discounted expected marginal disutility of labor.

2.3 Money Demand

As in Dotsey, King, and Wolman (1999), the money demand function is given by

$$\ln \frac{M_t}{P_t} = \ln c_t - \eta R_t, \tag{28}$$

where M_t is the quantity of money, $\eta \geq 0$, and R_t is the net nominal interest rate, which is defined by

$$\frac{1}{1+R_t} = \beta E_t \left(\frac{\lambda_{t+1}}{\lambda_t} \frac{P_t}{P_{t+1}} \right) = \beta E_t \left(\frac{\lambda_{t+1}}{\lambda_t} \frac{1}{\Pi_{t+1}} \right). \tag{29}$$

Here, Π_{t+1} is the gross inflation rate.[10]

[10] See Dotsey and King (2006) for the rationale for the use of this type of the money demand function. The money demand function of (28) can be derived from the money-in-the-utility model with a specific utility function, as shown in, for example, Walsh (2010).

3. Parameter Values

The third column of table 1 lists the parameter values for the benchmark model. The values are similar to those used in previous studies, such as Huang and Liu (2002) and Christiano, Eichenbaum, and Evans (2005). The length of a period is one quarter. The annual real interest rate is 4 percent and $\beta = 0.99$. The exponent of labor ζ is 2.0, implying a Frisch labor supply elasticity of 1.0. The composite labor supplied at the steady state n^{ss} is 30 percent of the total time endowment (normalized to one), which implies $\chi = 2.46$. The elasticity of output with labor α is 0.64. The elasticity of demand for differentiated goods ϵ^p and that for differentiated labor services ϵ^w are 6.0, generating 20 percent markup rates under flexible prices and wages.[11] The interest semi-elasticity of money demand η is 4.0, implying that a 1-percentage-point increase in the *annualized* nominal interest rate leads to a 1 percent reduction in real money balances, which is in line with the estimate by Christiano, Eichenbaum, and Evans (2005).[12] I assume 3 percent annual inflation at the steady state, which is close to the average inflation for the last two decades in the United States. Thus, the quarterly steady-state inflation rate $\bar{\Pi}$ and money growth rate $\bar{\mu}$ are $1.03^{0.25}$.

As for the distribution of price-setting costs, I follow Dotsey, King, and Wolman (1999) in assuming a flexible distributional family:

$$\xi^p(x) = B^p \frac{\arctan(b^p x - d^p \pi) + \arctan(d^p \pi)}{\arctan(b^p - d^p \pi) + \arctan(d^p \pi)}, \tag{30}$$

where $x \in [0, 1]$ and ξ^p is the inverse of G^p. For illustrative purposes, the benchmark model uses a shape similar to that assumed by Dotsey, King, and Wolman (1999) ($b^p = 16$ and $d^p = 2$, figure 1). The maximum cost B^p is adjusted to produce the average price duration

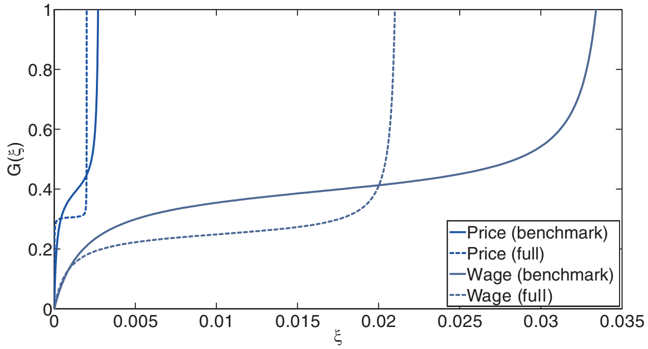
[11] Huang and Liu (2002) set $\epsilon^p = 10$, whereas Christiano, Eichenbaum, and Evans (2005) estimate $\epsilon^p = 6$ in their benchmark model. For ϵ^w, Huang and Liu (2002) use 2–6, whereas Christiano, Eichenbaum, and Evans (2005) set it at 21.

[12] I also solved the model with a higher interest semi-elasticity, $\eta = 17.65$, which is the value used by Dotsey, King, and Wolman (1999). The results did not change substantially relative to those under the baseline calibration.

Table 1. Parameter Values

Parameter	Description	Value	
		Benchmark	**Full**
β	Discount Factor	0.99	Same
ζ	Exponent on Labor	2.0	Same
χ	Disutility of Labor	2.46	3.19
α	Elasticity of Output with Labor	0.64	Same
ϵ^p	Elasticity of Demand for Goods	6.0	Same
ϵ^w	Elasticity of Demand for Labor Services	6.0	Same
η	Interest Semi-elasticity of Money Demand	4.0	Same
$\bar{\Pi}$ $(\bar{\mu})$	Steady-State Inflation (Money Growth) Rate	$1.03^{0.25}$	Same
(B^p, b^p, d^p)	Distribution of Price-Setting Costs	(0.0027,16,2)	(0.0020,360,35)
(B^w, b^w, d^w)	Distribution of Wage-Setting Costs	(0.0334,16,2)	(0.0210,34,2.7)
δ	Capital Depreciation Rate	NA	0.025
b	Habit	NA	0.65
σ_a	Capital Utilization Costs	NA	0.01
ψ	Capital Adjustment Costs	NA	10
ρ_R	Interest Rate Coefficient for the Interest Rate Rule	NA	0.80
ρ_Π	Inflation Coefficient for the Interest Rate Rule	NA	0.63
ρ_y	Output Coefficient for the Interest Rate Rule	NA	0.25
σ_R	Std. of Monetary Policy Shock	NA	0.000625
ρ_{μ^p}	Persistence of Price Markup	NA	0.94
θ_{μ^p}	MA Price Markup	NA	0.77
σ_{μ^p}	Std. of Price Markup Shock	NA	0.0014
ρ_{μ^w}	Persistence of Wage Markup	NA	0.97
θ_{μ^w}	MA Wage Markup	NA	0.91
σ_{μ^w}	Std. of Wage Markup Shock	NA	0.002
ρ_g	Persistence of Aggregate TFP	NA	0.95
σ_g	Std. of Aggregate TFP Shock	NA	0.006

Figure 1. Distributions of Price-Setting and Wage-Setting Costs



of three quarters at the steady state.[13] The degree of price rigidity is similar to that observed in micro-level data and that estimated using aggregate data.[14] At the steady state, 32.9 percent of prices are adjusted in any given quarter. This quarterly frequency of price changes is comparable to the monthly frequency of price changes of 9–12 percent reported by Nakamura and Steinsson (2008).

For the benchmark model, the shape of the distribution of wage-setting costs is the same as that of the distribution of price-setting costs (figure 1). Specifically, the distribution of wage-setting costs is

$$\xi^w(x) = B^w \frac{\arctan(b^w x - d^w \pi) + \arctan(d^w \pi)}{\arctan(b^w - d^w \pi) + \arctan(d^w \pi)}, \tag{31}$$

[13]The steady state is found by solving non-linear equations for equilibrium conditions. As in Dotsey, King, and Wolman (1999), the number of price vintages J is endogenously determined so that all the firms in the Jth price vintage choose to change their price. Similarly, the number of wage vintages Q is determined so that all the households in the Qth wage vintage choose to reset their wage. At the steady state, $J = 6$ and $Q = 9$.

[14]Analyzing micro-level data, Nakamura and Steinsson (2008) find that the mean (median) price duration is about eleven to thirteen (eight to eleven) months for 1988–2005 in the United States, whereas Bils and Klenow (2004) report a median duration of five and a half months for 1995–97. Estimating a New Keynesian model with the U.S. aggregate data, Christiano, Eichenbaum, and Evans (2005) find the average price spell of 2.3 quarters for 1965–95, while Smets and Wouters (2007) find that it is 3.7 quarters for 1981–2004.

where $x \in [0,1]$, ξ^w is the inverse of G^w, $b^w = 16$, and $d^w = 2$. The maximum cost B^w is adjusted to generate the average wage spell of 3.8 quarters at the steady state, which is in line with the estimates using micro-level and macro-level data.[15] At the steady state, 26.6 percent of wages are adjusted in any given quarter. This quarterly frequency of wage changes is in line with that estimated by Barattieri, Basu, and Gottschalk (2014).[16]

4. Impulse Responses to Monetary Shocks

This section compares the response to monetary shocks under state-dependent and time-dependent wage setting and examines how state dependency influences the transmission of monetary disturbances.[17] In order to analyze the role of price setting, I compare state-dependent and time-dependent wage setting under both state-dependent and time-dependent pricing. Specifically, the following four cases are compared: (i) state-dependent price setting and state-dependent wage setting (SS); (ii) state-dependent price setting and time-dependent wage setting (ST); (iii) time-dependent price setting and state-dependent wage setting (TS); and (iv) time-dependent price setting and time-dependent wage setting (TT). These four models use the same parameter values set as in the previous section and hence have the identical steady state, including the frequency of price and wage adjustments. However, the models respond to monetary disturbances in different ways. Under state-dependent setting, households (firms) optimally change the timing of wage (price) adjustments in response to monetary shocks. Hence, there

[15]Examining micro-level data, Barattieri, Basu, and Gottschalk (2014) report that the average wage duration is 3.8–4.7 quarters in the United States for 1996–99. Using the U.S. aggregate data, Smets and Wouters (2007) estimate that the average wage duration is about 3.8 quarters for 1981–2004. In contrast, Christiano, Eichenbaum, and Evans (2005) estimate that the average wage duration is 2.8 quarters for 1965–95. I calibrated my model to this lower wage stickiness and found no significant change relative to the results under the baseline calibration.

[16]The implied price-setting and wage-setting costs are small. At the steady state, 0.04 percent and 0.25 percent of total labor are used for price and wage adjustments, respectively.

[17]Following Dotsey, King, and Wolman (1999), I first linearize the model around the steady state and then use the method of King and Watson (1998, 2002). I am grateful to the authors for making their computer codes available.

are endogenous movements in the frequency of wage (price) adjustments. In contrast, under time-dependent setting, households (firms) cannot change when to adjust their wage (price) and must follow the steady-state timing. Therefore, the frequency of adjustments remains unchanged at its steady-state level.

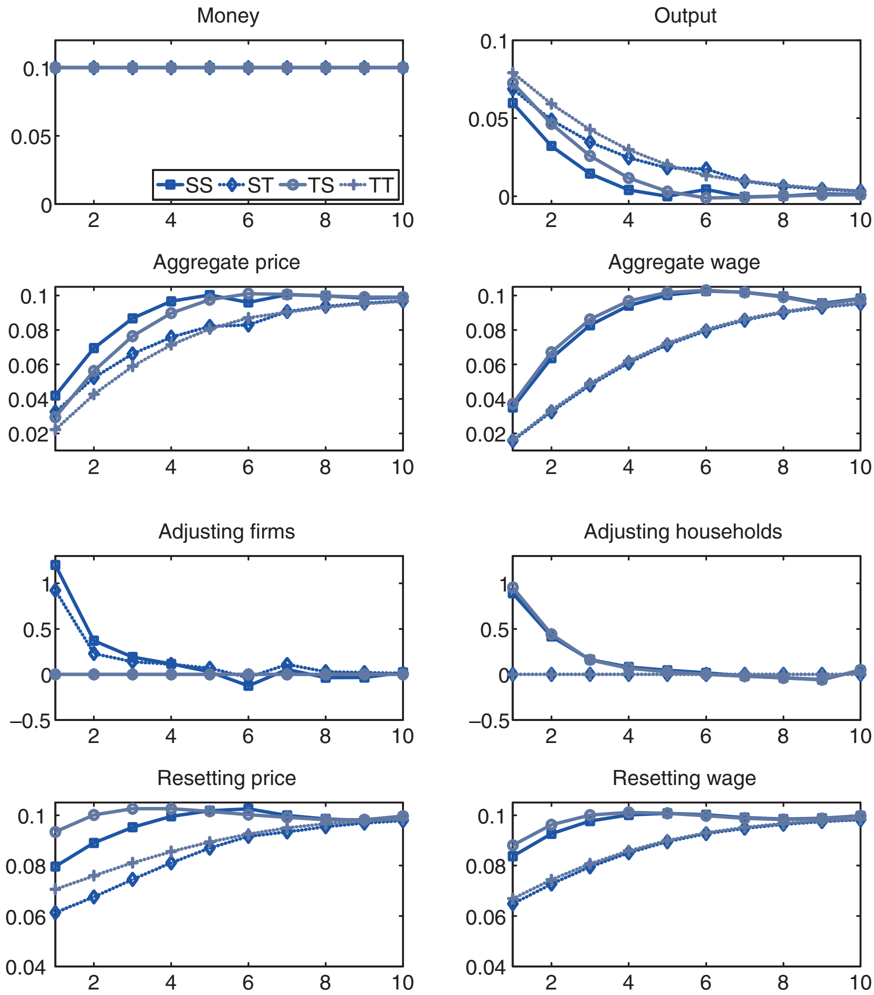
I assume that a shock occurs in period 1 and that the quantity of money M_t increases by 0.1 percent permanently, as shown in the upper-left graph in figure 2.[18] As shown in the upper-right graph in figure 2, under both state-dependent and time-dependent wage setting, output increases temporarily following the expansionary monetary shock, as in typical New Keynesian models with nominal wage stickiness (see Huang and Liu 2002 and Christiano, Eichenbaum, an Evans 2005). However, state dependency in wage setting reduces the increase in output compared with time-dependent setting. As an example, compare the two under state-dependent pricing (SS versus ST). Under SS, output increases by 0.06 percent in period 1 and returns to almost the pre-shock level by period 4. Hence, the real impact of the monetary shock almost disappears within a year. In contrast, the increase in output is larger and more persistent under ST. Output increases by 0.07 percent initially and remains above the pre-shock level for more than two years. A similar pattern is observed under time-dependent pricing (TS versus TT).

Next, in order to understand the impact of state dependency in wage setting shown above, micro-level wage adjustments are examined. Since all adjusting households choose the same wage in the present model, micro-level wage adjustments are largely described by the fraction of households adjusting their wage and the resetting wage chosen by those adjusting households.

The two lower-right graphs in figure 2 present the responses of these two dimensions of wage adjustments. Following the expansionary monetary shock, the aggregate price, consumption, and labor

[18] In response to a large shock, all the firms and households in the second-to-last ($J-1$th and $Q-1$th) vintages choose to adjust their price and wage respectively, changing the numbers of price and wage vintages. I analyze a small shock to avoid this problem. Since I solve my model with a linearized method, the size of the shock does not matter for the impact of state dependency in price and wage setting on monetary non-neutralities. It would be interesting to solve the model with a non-linear method, but I leave it to future research. Further, I choose the size of the monetary shock more carefully for the full model in section 5.

Figure 2. Permanent Increase in Money—Benchmark Model



Notes: The horizontal axis shows quarters. The vertical axis is the percent deviation (percentage points deviation for adjusting firms and households) from the steady state.

hours increase. If households do not raise their wage, their real wage falls, while the marginal rate of substitution of leisure for consumption rises. Hence, the fraction of households raising their wage increases under state-dependent setting. For example, under SS, the fraction rises by 0.89 of a percentage point in period 1. In contrast, by construction, the fraction does not increase under time-dependent setting (ST). Adjusting households also set a higher wage under state-dependent setting than under time-dependent setting. The resetting wage rises by 0.084 percent under SS, whereas it rises only by 0.065 percent under ST.

Why does state dependency in wage setting lead to a higher resetting wage? Suppose instead that adjusting households set the same wage and the resetting wage increases by the same amount under state-dependent and time-dependent wage setting. Then, since state dependency in wage setting gives a higher number of adjusting households, the aggregate nominal wage must rise more quickly under state-dependent than under time-dependent setting. The quicker rise in the aggregate wage has two opposing effects on the optimal resetting wage, as indicated by (27). On one hand, it raises the optimal resetting wage: Because households' labor hours increase with the aggregate wage, as shown in (17), adjusting households need to raise their wage more strongly in order to reduce their labor hours. On the other hand, in response to the higher aggregate wage, firms raise their price more quickly. This reduces the increases in consumption and aggregate labor hours, dampening the rise in the optimal resetting wage. In addition, since households can choose the timing of wage adjustments, households under state-dependent wage setting have less incentive to front-load wage increases than those under time-dependent setting. However, under parameter values commonly used in the literature, the relative wage effect dominates the other effects. Hence, the resetting wage is higher under state-dependent wage setting than under time-dependent wage setting.

Since more households raise their wage and those households set a higher wage, the aggregate wage rises more quickly and firms also raise their price more quickly under state-dependent wage setting than under time-dependent wage setting. As a result, state dependency in wage setting reduces the real impacts of monetary shocks.

The relative wage effect is also the key to the relationship between money non-neutralities and the elasticity of demand for differentiated labor services. Figure 3 presents impulse responses to the expansionary monetary shock introduced above for three values of the elasticity: $\epsilon^w = 3$, 6 (benchmark), and 8.[19] The graphs on the left side show the results when both price and wage setting are state dependent (SS), while those on the right show the results when only wage setting switches to time dependency (ST).[20]

Under time-dependent wage setting (ST), monetary non-neutralities increase as the elasticity of demand for differentiated labor ϵ^w rises. This result is the same as that under conventional time-dependent wage setting, such as Taylor-style setting (e.g., Huang and Liu 2002). When ϵ^w is high, households' labor hours quickly decrease with their wage relative to the aggregate wage, and adjusting households find it optimal to raise their wage mildly. Hence, the rise in the resetting wage is decreasing in ϵ^w. Since the fraction of households raising their wage does not change under time-dependent setting, the aggregate wage rises more slowly and money non-neutralities become larger for a higher ϵ^w.

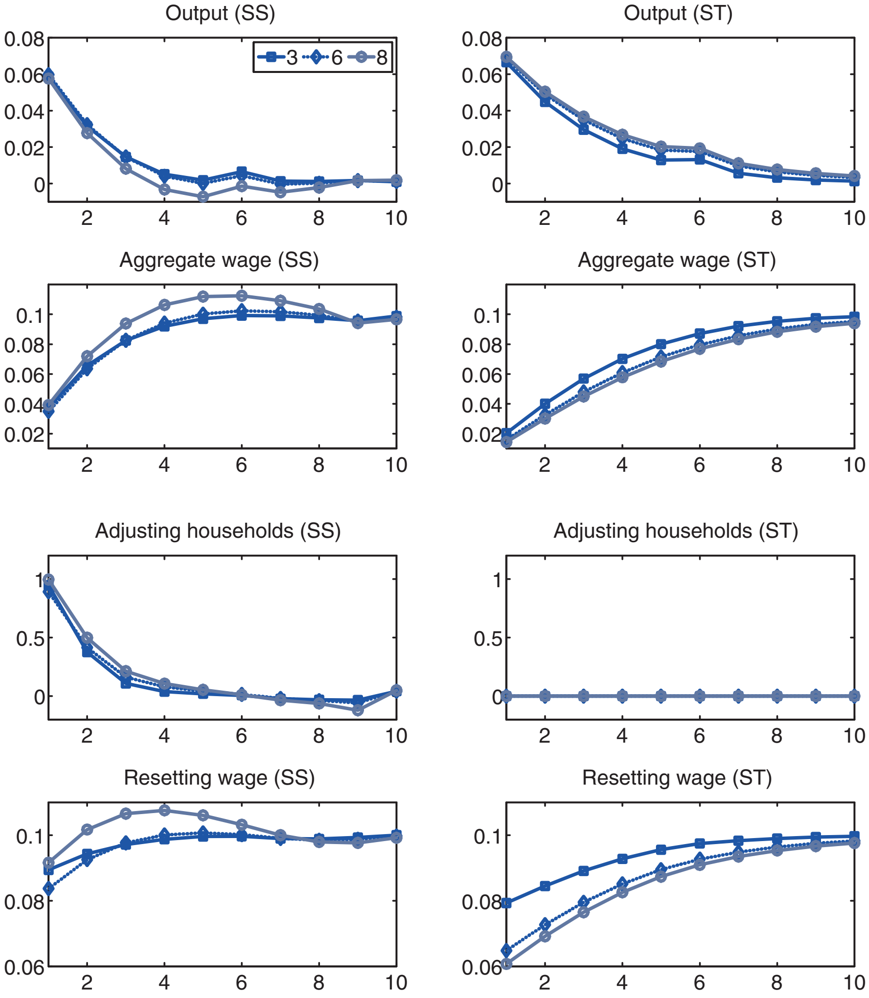
The relationship is overturned under state-dependent wage setting (SS), and the response of output decreases as the elasticity of demand for differentiated labor ϵ^w rises. If households do not raise their wage under a high ϵ^w, their labor hours and thus the marginal rate of substitution of leisure for consumption substantially increase. Hence, more households choose to raise their wage under a higher ϵ^w. As for the resetting wage, two effects compete. On one hand, when ϵ^w is higher, households find it optimal to raise their wage more mildly relative to the aggregate wage. On the other hand, the aggregate wage rises more quickly because a larger fraction of households raise their wage. Under the parameter values considered here, the resetting wage first decreases and then increases with ϵ^w. Overall, under a higher ϵ^w, the aggregate wage rises more quickly and monetary non-neutralities become smaller.

To summarize, state dependency in wage setting decreases the real impacts of monetary disturbances compared with

[19] Other parameters keep their benchmark value, except that the maximum wage-setting cost B^w and the disutility of labor χ are adjusted to maintain the average wage duration (3.8 quarters) and the composite labor supplied at the steady state n^{ss} (0.3).

[20] The results do not change significantly when price setting is made time dependent (TS versus TT).

Figure 3. Elasticity of Demand for Differentiated Labor—Benchmark Model



Notes: The horizontal axis shows quarters. The vertical axis is the percent deviation (percentage points deviation for adjusting firms and households) from the steady state.

time-dependent setting. Further, monetary non-neutralities could decrease with the elasticity of demand for differentiated labor services under state-dependent wage setting, while the opposite relationship holds under time-dependent setting.

5. State Dependency in Wage Setting in the United States

This subsection quantifies the impact of state dependency in wage setting on monetary non-neutralities and on the trade-off between stabilizing the output gap and inflation for the U.S. economy. To this end, I modify the benchmark model with various real-side features and shocks. I then calibrate the distributions of price-setting and wage-setting costs to the patterns of price and wage adjustments observed in the U.S. micro-level data.

5.1 Full Model

The household side is modified as follows. Households' preferences include habit formation, and the momentary utility function is given by $\ln[c_t(h) - bc_{t-1}(h)] - \chi n_t(h)^\zeta$, where $b \in [0, 1]$. There is capital accumulation, and as in Huang and Liu (2002), households choose the amount of capital that they carry into the next period $\bar{k}_{t+1}(h)$ subject to quadratic adjustment costs $\psi[\bar{k}_{t+1}(h) - \bar{k}_t(h)]^2/\bar{k}_t(h)$, where $\psi > 0$. Further, households choose the amount of capital services that they supply $k_t(h) = u_t(h)\bar{k}_t(h)$ by choosing capital utilization rate $u_t(h)$ subject to costs $a(u_t(h))\bar{k}_t(h)$, as in Christiano, Eichenbaum, and Evans (2005). Hence, households face the budget constraint:

$$\begin{aligned} q_t k_t(h) &+ \frac{W_t(h)n_t(h)}{P_t} + \frac{M_{t-1}(h)}{P_t} + \frac{B_{t-1}(h)}{P_t} + \frac{D_t(h)}{P_t} \\ &= c_t(h) + \bar{k}_{t+1}(h) - (1-\delta)\bar{k}_t(h) + \psi\frac{[\bar{k}_{t+1}(h) - \bar{k}_t(h)]^2}{\bar{k}_t(h)} \\ &\quad + a(u_t(h))\bar{k}_t(h) + \frac{\delta_{t+1,t}B_t(h)}{P_t} + \frac{M_t(h)}{P_t} + w_t\xi_t^w(h)I_t(h), \quad (32) \end{aligned}$$

where $\delta \in [0, 1]$ is the capital depreciation rate. As in Justiniano, Primiceri, and Tambalotti (2010) and Katayama and Kim (2013), the wage markup rate, $\mu_t^w \equiv \epsilon_t^w/(\epsilon_t^w - 1)$, changes stochastically and follows

$$\ln \mu_t^w = (1-\rho_{\mu^w}) \ln \mu^w + \rho_{\mu^w} \ln \mu_{t-1}^w + \varepsilon_{\mu^w,t} - \theta_{\mu^w} \varepsilon_{\mu^w,t-1}, \quad (33)$$

where $\rho_{\mu^w} \in [0,1), \theta_{\mu^w} \in [0,1), \mu^w \equiv \epsilon^w/(\epsilon^w - 1)$ is the steady-state wage markup rate, and $\varepsilon_{\mu^w,t}$ is a wage markup shock that is independently and identically distributed as $N(0, \sigma_{\mu^w}^2)$.

The firm side of the model is changed as follows. There are shocks to aggregate total factor productivity (TFP) g_t and the production function is

$$y_t(z) = g_t k_t(z)^{1-\alpha} n_t(z)^{\alpha}, \quad (34)$$

where g_t follows an AR(1) process:

$$\ln g_t = \rho_g \ln g_{t-1} + \varepsilon_{g,t}, \quad (35)$$

where $\rho_g \in [0,1)$ and $\varepsilon_{g,t}$ is a TFP shock that is independently and identically distributed as $N(0, \sigma_g^2)$. Further, q_t in (3) is the real rental rate of capital services. The price markup rate, $\mu_t^p \equiv \epsilon_t^p/(\epsilon_t^p - 1)$, is subject to exogenous shocks. Specifically, as in Justiniano, Primiceri, and Tambalotti (2010), it follows that

$$\ln \mu_t^p = (1-\rho_{\mu^p}) \ln \mu^p + \rho_{\mu^p} \ln \mu_{t-1}^p + \varepsilon_{\mu^p,t} - \theta_{\mu^p} \varepsilon_{\mu^p,t-1}, \quad (36)$$

where $\rho_{\mu^p} \in [0,1), \theta_{\mu^p} \in [0,1), \mu^p \equiv \epsilon^p/(\epsilon^p - 1)$ is the steady-state price markup rate, and $\varepsilon_{\mu^p,t}$ is a price markup shock that is independently and identically distributed as $N(0, \sigma_{\mu^p}^2)$.

Lastly, monetary policy is characterized by the interest rate rule in the spirit of Levin, Wieland, and Williams (1998):

$$R_t = (1-\rho_R)\bar{R} + \rho_R R_{t-1} + \rho \ln \frac{\Pi_t}{\bar{\Pi}} + \rho_y \ln \frac{y_t^g}{y_{t-1}^g} + \varepsilon_{R,t}, \quad (37)$$

where $\rho_R, \rho, \rho_y \geq 0, y_t^g$ is the output gap, and $\varepsilon_{R,t}$ is a monetary shock that is independently and identically distributed as $N(0, \sigma_R^2)$.[21]

[21] As in Justiniano, Primiceri, and Tambalotti (2010), the output gap is defined as the deviation of the actual output from the output that would be realized in the absence of price/wage stickiness and price/wage markup shocks.

5.2 Parameter Values

The last column of table 1 lists parameter values for the full model. I first choose the parameter values for the state-dependent price-setting and wage-setting model (SS) and then use the same parameter values for the other three models (ST, TS, and TT). The parameters appearing in the model of the previous section inherit their original values, except for the disutility of labor χ, which is adjusted to maintain the steady-state labor ($n^{ss} = 0.3$), and the parameters on the distributions of price-setting and wage-setting costs. The capital depreciation rate δ is 0.025. I set the habit parameter $b = 0.65$, which is the estimate by Christiano, Eichenbaum, and Evans (2005). I also follow Christiano, Eichenbaum, and Evans (2005) in setting the capital utilization cost: $\bar{u} = 1, a(1) = 0$, and $\sigma_a = a^{''}(1)/a^{'}(1) = 0.01$. The parameterization generates a peak response of the capital utilization rate to a monetary shock that is roughly equal to that of output, which is in line with their finding. Further, I set the capital adjustment cost parameter $\psi = 10$ so that, as in Dotsey and King (2006), the peak response of investment to a monetary shock is a bit larger than twice that of output, which is also consistent with the results in Christiano, Eichenbaum, and Evans (2005).

For the baseline coefficients of the interest rate policy rule of (37), I use the values estimated by Levin, Wieland, and Williams (1998) for the U.S. economy: $\rho_R = 0.80$, $\rho = 0.63$, and $\rho_y = 0.25$.[22] I set $\sigma_R = 0.000625$ so that a one-standard-deviation monetary policy shock corresponds to a 25-basis-point change in the annualized interest rate, as in Gornemann, Kuester, and Nakajima (2014).[23] For the price and wage markup processes, I use the values estimated by Justiniano, Primiceri, and Tambalotti (2010): $\rho_{\mu^p} = 0.94, \theta_{\mu^p} = 0.77, \sigma_{\mu^p} = 0.0014, \rho_{\mu^w} = 0.97, \theta_{\mu^w} = 0.91$, and $\sigma_{\mu^w} = 0.002$. For the aggregate TFP process, I use the conventional value for persistence ($\rho_g = 0.95$) and then adjust the volatility σ_g so that my SS model reproduces the volatility of (HP-filtered) output in the U.S.

[22]See equation (1) of Levin, Wieland, and Williams (1998). The output coefficient is divided by four since the estimated equation is based on the annualized interest rate.

[23]The results of the present section are robust to the size of σ_R. For example, even when σ_R doubles, they did not change substantially.

Table 2. Calibration of the Distribution of Wage-Setting Costs

	U.S. Data	Model
Average Wage Spell (Quarters)	3.8	4.0
Fraction of Wages Not Changed for a Year (%)	25	23
$\sigma_{fraction}/\sigma_y$	4.5	4.5

data (1.7 percent). The result is $\sigma_g = 0.006$, which is close to the conventional value used in Cooley and Prescott (1995) and others.

I use the distribution of price-setting costs similar to that used by Klenow and Kryvtsov (2005, 2008). They find that the volatility of the U.S. inflation is mostly driven by the volatility of the average price change and the volatility of the fraction of price changes plays a minor role. This finding indicates that the distribution of price-setting costs must be similar to the Calvo-type distribution under which almost all firms draw either zero or the maximum price-setting costs. In addition to this, I target an average price spell of 3.0 quarters and a quarterly frequency of price adjustments of about 33 percent at the steady state. These two targets are motivated by the estimates by Nakamura and Steinsson (2008). Figure 1 shows the selected distribution.[24]

The distribution of wage-setting costs is chosen targeting the three statistics on micro-level wage adjustments shown in table 2. First, the average wage duration is 3.8 quarters at the steady state, which is consistent with the finding of Barattieri, Basu, and Gottschalk (2014) and close to the conventional estimate (see Taylor 1999). The other two targets involve the fraction of wages not changed for a year. I focus on this variable because wage data are

[24]In contrast, Costain and Nakov (2011a, 2011b) choose the distribution of price-setting costs by targeting the empirical size distribution of price changes. Since there are a large number of small price changes, the selected distribution is concave, which implies that most firms draw a relatively small menu cost. See also Nakov and Thomas (2014). I solved my model with a similar concave distribution of price-setting costs. Compared with the distribution used here, which essentially shuts down state dependency in price setting, monetary non-neutralities become smaller. However, the impact of state dependency in *wage* setting on monetary non-neutralities is largely unchanged.

typically collected annually and most available evidence for state dependency in wage setting is about the fraction of those long-term rigid wages.[25] Hence, the second target is the long-run average fraction of wages not changed for a year. I target 25 percent based on the estimate by Barattieri, Basu, and Gottschalk (2014).[26]

The third target is the volatility of the fraction of wages not changed for a year. I compute the actual volatility using the wage rigidity meter of the Federal Reserve Bank of San Francisco between 1997:Q3 and 2013:Q4. The meter is released monthly and I take the number of the middle month of a quarter as the quarterly number. The log of the series is taken and detrended using the Hodrick-Prescott filter of a smoothing parameter of 1,600. The resulting volatility is 4.5 times as large as the output volatility.[27]

As figure 1 shows, the distribution is similar to the Calvo-type distribution in that a large number of households draw either small or large costs. However, there are some households drawing intermediate costs and their adjustment decisions vary with economic states, generating some state dependency in wage setting. Accordingly, as table 2 shows, the calibrated model reasonably reproduces the data moments.[28] In contrast, if the distribution of the benchmark model is assumed, then the fraction of wages not changed for a year shows a counterfactually high volatility (16.8). If the shape of the distribution of price-setting costs is assumed, then the volatility becomes too low (0.2) compared with the data value.

[25] An example is Card and Hyslop (1997). For the United States, a notable exception is Barattieri, Basu, and Gottschalk (2014), who compute the quarterly frequency of wage adjustments. However, their data cover a relatively short period (1996–99), and it is difficult to compute the volatility of the quarterly frequency of wage adjustments.

[26] The wage rigidity meter released by the Federal Reserve Bank of San Francisco implies a lower fraction: It is about 13 percent between August 1997 and December 2013. Given the average wage duration of about a year, it is hard to reproduce this in the model. Hence, I target the finding of Barattieri, Basu, and Gottschalk (2014).

[27] The data are discontinuous in 1997:Q2. While the data for all workers are used here, the volatility does not change very significantly when computed separately for hourly and non-hourly workers (4.3 for hourly workers and 6.0 for non-hourly workers).

[28] The wage rigidity meter is the twelve-month moving average of the fraction of wages not changed for a year. Therefore, I take the five-quarter moving average for the model statistic to maintain the comparability.

5.3 Impulse Responses to Monetary Policy Shocks

As in the benchmark model, the four price-setting and wage-setting models are compared: SS, ST, TS, and TT. These four models have the identical steady state, including the steady-state frequency of price and wage adjustments. However, they respond to monetary disturbances in different ways.

Figure 4 presents the response to an expansionary monetary shock of one standard deviation ($\sigma_R = 0.000625$) or a negative shock of 25 basis points to the interest rate. As shown, the state-dependent and time-dependent wage-setting models generate quite similar responses. Although state dependency in wage setting reduces monetary non-neutralities, the impact is mild. For example, the cumulative response of output for ten quarters after the shock decreases only by 9 percent as wage setting switches from time to state dependency under state-dependent pricing (SS versus ST). Given the weak state dependency in wage setting, monetary non-neutralities increase with the elasticity of demand for differentiated labor under state-dependent wage setting, as under time-dependent wage setting. Other real and nominal aggregate variables also move in a similar way under state-dependent and time-dependent wage setting.[29]

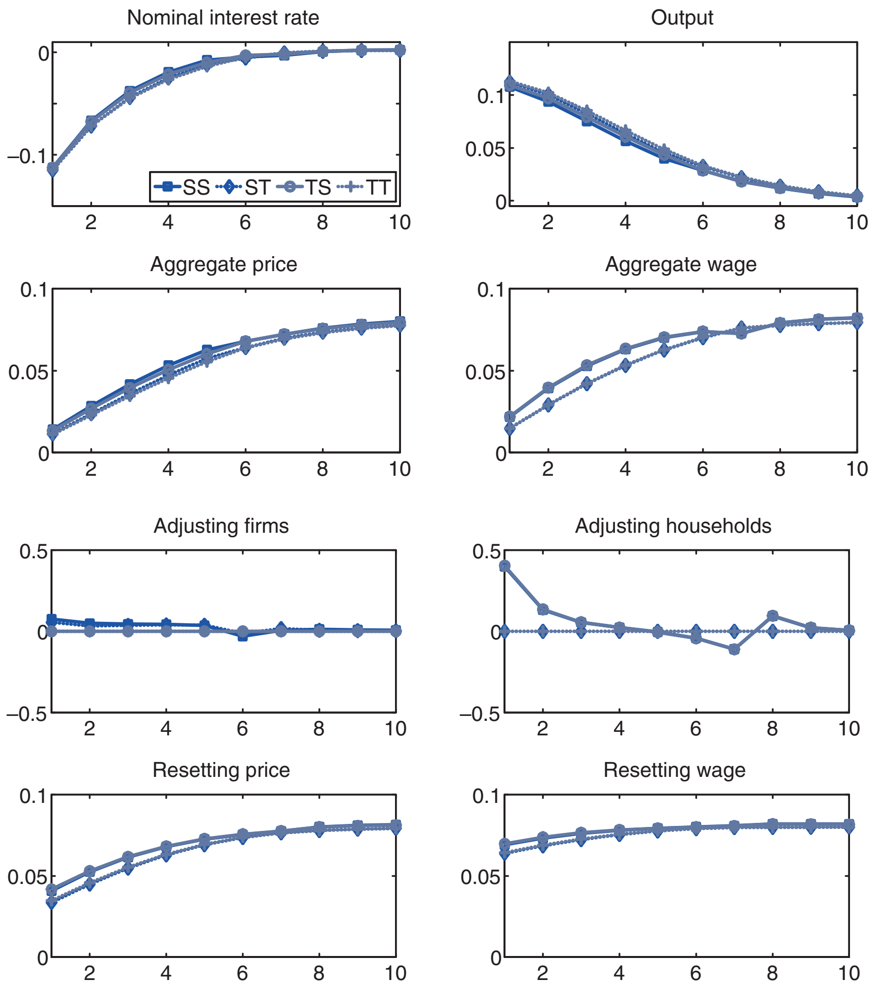
As for micro-level wage adjustments, the fraction of adjusting households increases by around 0.40 percentage point at the onset of the shock under state-dependent price and wage setting (SS). The increase is small relative to the increase in output of 0.11 percent.[30] Because of the small increase in the extensive margin, the resetting wage is also only slightly higher under state-dependent wage setting than under time-dependent wage setting. As a result, the rises in the aggregate wage are similar between the two wage-setting cases.

What is responsible for the moderate impact of state dependency in wage setting? The answer is the distribution of wage-setting costs. If the distribution of the full model is used for the benchmark model of the previous section, then state dependency in wage setting reduces monetary non-neutralities only by 12 percent, which is similar to that in the full model. While the distribution of price-setting

[29] These results are available upon request.

[30] In the benchmark SS model, the fraction of adjusting households initially increases by 0.90 percentage points, while output increases by 0.06 percent.

Figure 4. Expansionary Monetary Shock—Full Model



Notes: The horizontal axis shows quarters. The vertical axis is the percent deviation (percentage points deviation for the nominal interest rate and adjusting firms and households) from the steady state. The interest rate is annualized.

costs, habit formation, capital adjustment costs, and the capital utilization affect the impulse responses to monetary shocks, they do not significantly affect the impact of state dependency in *wage* setting on monetary non-neutralities.

The results of this subsection imply that when calibrated to the variation in the wage rigidity in the data, the state dependency in wage setting considered here has a minor impact on the response to monetary disturbances in the United States and the time-dependent wage-setting models approximate the state-dependent models reasonably well.

5.4 Trade-off between Output and Inflation Stabilization

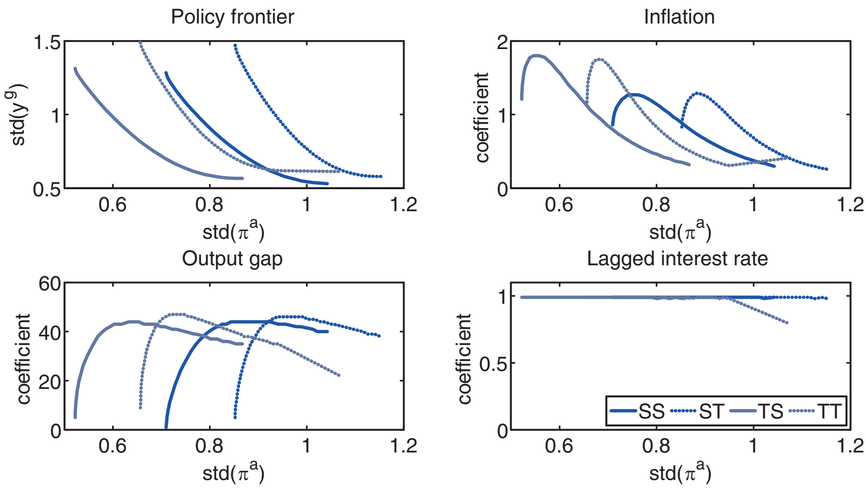
Next, I analyze how state dependency in wage setting affects the trade-off between the volatility of the output gap and the volatility of inflation by computing the policy frontiers for my models.[31] Specifically, as in Levin, Wieland, and Williams (1998), I search for the coefficients of the interest rate rule of (37) (ρ_R, ρ, ρ_y) that minimize $\lambda Var(y_t^g) + (1-\lambda)Var(\pi_t^a)$, where $\lambda \in [0,1]$ reflects the central bank's preference, Var is the unconditional variance, and π_t^a is the annualized inflation rate.[32] As in Levin, Wieland, and Williams (1998), I set an upper bound on the variance of the change in the interest rate, $Var(R_t - R_{t-1})$. This upper bound is set to the variance implied by the baseline interest rate policy rule and hence it is different among the four cases.

The upper-left graph in figure 5 shows the policy frontiers for the four specifications (SS, ST, TS, and TT). As in Levin, Wieland, and Williams (1998) and Erceg, Henderson, and Levin (2000), the policy frontiers are downward sloping. Hence, there is a trade-off between stabilizing the output gap and inflation. As for the difference among the four frontiers, state dependency in wage setting shifts the frontier leftward. The effect is similar to that of lowering wage stickiness in a time-dependent sticky price and sticky wage model (e.g., Gali 2008). In that model, given an interest rate rule, more flexible wages lead to a lower combination of the volatility of the output gap and inflation. In the present model, state dependency in

[31] I thank an anonymous referee for suggesting this exercise.

[32] While Levin, Wieland, and Williams (1998) include the lagged output gap in estimation, they compute the policy frontier using an interest rate rule without the lagged output gap. I include it because without it, my SS model often has no solution. As in Levin, Wieland, and Williams (1998), I also only consider an interest rate rule that leads to a unique equilibrium. I focus on $\rho_R \in [0, 0.99]$.

Figure 5. Policy Frontiers and the Coefficients of the Optimal Interest Rate Rule

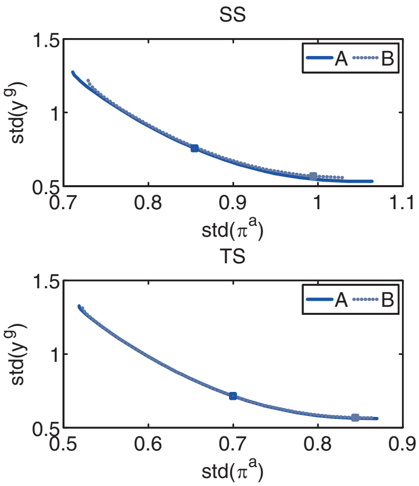


wage setting essentially makes wage adjustments more flexible compared with time-dependent setting. The effect of state-dependent pricing in the present model is also similar to that of lowering price stickiness in a typical time-dependent model: More price flexibility increases the variance of inflation, shifting the policy frontier rightward.

The remaining graphs in figure 5 show the coefficients of the interest rate rule against the inflation volatility. In all of the four cases, it is optimal to smooth the interest rate strongly and respond to both the output gap and inflation. Analyzing various models, Levin, Wieland, and Williams (1998) find that those are robust features of the optimal interest rate rule. The finding here indicates that their conclusion holds for the present model both with and without state dependency in price and wage setting.

Next, I examine the robustness of the optimal interest rate rule to price-setting and wage-setting specifications, conducting an exercise similar to that in section 6 of Levin, Wieland, and Williams (1998). Specifically, I take the optimal policies for $\lambda = 0.25$ and 0.75 in TT and call them policies A and B, respectively. I then compute two policy frontiers for each of the four models (SS, ST, TS, and

Figure 6. Robustness of the Interest Rate Rule



TT), setting the upper bound of the variance of the change in the interest rate to that implied by policies A and B.[33]

Figure 6 shows the results. The squares indicate the output-inflation volatility under policies A and B. In all the models, the volatility of the output gap and inflation implied by policies A and B are very close to the respective policy frontiers, suggesting that policies A and B perform well for all of the models.[34] As table 3 shows, policies A and B incur a small loss relative to the optimal rule even for the models with state dependency in price and wage setting.

The results of this subsection suggest that the trade-off between the output and inflation volatility and hence implications for monetary policy are quite similar among different price-setting and wage-setting specifications. In all the cases considered, the optimal interest rate rule is characterized by smoothing the interest rate and

[33] I take the optimal rules for TT as the benchmark because previous studies typically analyze an interest rate policy rule under time-dependent sticky prices and sticky wages.

[34] For TT, the two policy frontiers coincide because the volatility of a change in the interest rate is the same under policies A and B. Further, the squares are on the policy frontiers.

Table 3. Loss by the Optimal Interest Rate Rule for TT

		Loss (%)
SS	A	0.94
	B	0.00
ST	A	0.11
	B	0.38
TS	A	1.18
	B	0.83

responding to the output gap and inflation. The optimal interest rate rule under time-dependent price and wage setting works well even when state dependency in price and wage setting is present.

6. Conclusion

While there is some evidence that the timing and frequency of wage adjustments vary with economic states, existing New Keynesian models abstract such state dependency in wage setting and exclusively assume exogenous frequency and timing under time-dependent wage setting. To fill this gap, the present paper has constructed a New Keynesian model including fixed wage-setting costs and has analyzed how state dependency in wage setting influences the transmission of monetary shocks. This paper has found that the real impacts of monetary shocks are reduced by state dependency in wage setting. However, when parameterized to reproduce the observed variation in the fraction of wages not changed for a year in the United States, the state-dependent wage-setting model shows a response to monetary shocks quite similar to that of the time-dependent model. The trade-off between output and inflation stabilization is also similar between the two models. In particular, the optimal interest rate rule for the time-dependent sticky wage model performs well for the state-dependent sticky wage model.

There are several directions for future research. First, it would be interesting to introduce idiosyncratic shocks into the model. While the present model is calibrated to match a certain feature of price and wage setting, in the absence of idiosyncratic shocks, it cannot reproduce some other features observed in the actual data.[35] Hence, an important remaining task is to examine the robustness of the results of the present paper using a model with idiosyncratic shocks. Second, it would be interesting to evaluate the importance of state dependency in wage setting for countries other than the United States. In particular, there are a large number of studies on micro-level wage adjustments in European countries, and the present model can be calibrated to their findings.[36] Third, the present model is a natural framework to consider optimal monetary policy beyond a simple interest rate rule. In particular, since Nakov and Thomas (2014) analyze optimal monetary policy under state-dependent pricing, it would be interesting to examine how their results change under state dependency in both price and wage setting. Lastly, state-dependent wage setting could be analyzed in other labor-market models than that analyzed here, such as models with efficiency wages and labor search and matching.[37]

References

Bakhshi, H., H. Kahn, and B. Rudolf. 2007. "The Phillips Curve under State-Dependent Pricing." *Journal of Monetary Economics* 54 (8): 2321–45.

Barattieri, A., S. Basu, and P. Gottschalk. 2014. "Some Evidence on the Importance of Sticky Wages." *American Economic Journal: Macroeconomics* 6 (1): 70–101.

Bils, M., and P. J. Klenow. 2004. "Some Evidence on the Importance of Sticky Prices." *Journal of Political Economy* 112 (5): 947–85.

Blanchard, O. J., and N. Kiyotaki. 1987. "Monopolistic Competition and the Effects of Aggregate Demand." *American Economic Review* 77 (4): 647–66.

[35]For example, there are only price and wage increases in the present model, while price and wage cuts are frequently observed in the actual data.

[36]Some examples are Fabiani et al. (2010), Walque et al. (2010), and Le Bihan, Montornes, and Heckel (2012).

[37]Cajner (2011) analyzes state-dependent wage setting in a model with labor search and matching.

Cajner, T. 2011. “Labor Market Frictions and Bargaining Costs: A Model of State-Dependent Wage Setting.” Mimeo.

Calvo, G. A. 1983. “Staggered Prices in a Utility-Maximizing Framework.” *Journal of Monetary Economics* 12 (3): 383–98.

Caplin, A., and J. Leahy. 1991. “State-Dependent Pricing and the Dynamics of Money and Output.” *Quarterly Journal of Economics* 106 (3): 683–708.

Caplin, A. S., and D. F. Spulber. 1987. “Menu Costs and the Neutrality of Money.” *Quarterly Journal of Economics* 102 (4): 703–25.

Card, D., and D. Hyslop. 1997. “Does Inflation ‘Grease the Wheels of the Labor Market’?” In *Reducing Inflation: Motivation and Strategy*, ed. C. D. Romer and D. H. Romer 71–114. Chicago: University of Chicago Press.

Christiano, L. J., M. Eichenbaum, and C. L. Evans. 2005. “Nominal Rigidities and the Dynamic Effects of a Shock to Monetary Policy.” *Journal of Political Economy* 113 (1): 1–45.

Cooley, T. F., and E. C. Prescott. 1995. “Economic Growth and Business Cycles.” In *Frontiers of Business Cycle Research*, ed. T. F. Cooley. Princeton, NJ: Princeton University Press.

Costain, J., and A. Nakov. 2011a. “Distributional Dynamics under Smoothly State-Dependent Pricing.” *Journal of Monetary Economics* 58 (6–8): 646–65.

———. 2011b. “Price Adjustments in a General Model of State-Dependent Pricing.” *Journal of Money, Credit and Banking* 43 (2–3): 385–406.

Daly, M., and B. Hobijn. 2014. “Downward Nominal Wage Rigidities Bend the Phillips Curve.” Working Paper No. 2013-08, Federal Reserve Bank of San Francisco.

Daly, M., B. Hobijn, and B. Lucking. 2012. “Why Has Wage Growth Stayed Strong?” Economic Letter No. 2012-10, Federal Reserve Bank of San Francisco.

Devereux, M. B., and H. E. Siu. 2007. “State Dependent Pricing and Business Cycle Asymmetries.” *International Economic Review* 48 (1): 281–310.

Dixon, H., and E. Kara. 2010. “Can We Explain Inflation Persistence in a Way that Is Consistent with the Microevidence on

Nominal Rigidity?" *Journal of Money, Credit and Banking* 42 (1): 151–70.

Dixon, H., and H. Le Bihan. 2012. "Generalised Taylor and Generalised Calvo Price and Wage Setting: Micro-Evidence with Macro Implications." *Economic Journal* 122 (May): 532–54.

Dotsey, M., and R. G. King. 2005. "Implications of State-Dependent Pricing for Dynamic Macroeconomic Models." *Journal of Monetary Economics* 52 (1): 213–42.

———. 2006. "Pricing, Production, and Persistence." *Journal of the European Economic Association* 4 (5): 893–928.

Dotsey, M., R. G. King, and A. L. Wolman. 1999. "State-Dependent Pricing and the General Equilibrium Dynamics of Money and Output." *Quarterly Journal of Economics* 114 (2): 655–90.

Erceg, C. J., D. W. Henderson, and A. T. Levin. 2000. "Optimal Monetary Policy with Staggered Wage and Price Contracts." *Journal of Monetary Economics* 46 (2): 281–313.

Fabiani, S., C. Kwapil, T. Room, K. Galuscak, and A. Lamo. 2010. "Wage Rigidities and Labor Market Adjustment in Europe." *Journal of the European Economic Association* 8 (2–3): 497–505.

Gali, J. 2008. Monetary Policy, Inflation, and the Business Cycle. Princeton, NJ: Princeton University Press.

Gertler, M., and J. Leahy. 2008. "A Phillips Curve with an Ss Foundation." *Journal of Political Economy* 116 (3): 533–72.

Golosov, M., and R. E. Lucas, Jr. 2007. "Menu Costs and Phillips Curves." *Journal of Political Economy* 115 (2): 171–99.

Gornemann, N., K. Kuester, and M. Nakajima. 2014. "Doves for the Rich, Hawks for the Poor? Distributional Consequences of Monetary Policy." Mimeo.

Huang, K. X. D., and Z. Liu. 2002. "Staggered Price-Setting, Staggered Wage-Setting, and Business Cycle Persistence." *Journal of Monetary Economics* 49 (2): 405–33.

Huang, K. X. D., Z. Liu, and L. Phaneuf. 2004. "Why Does the Cyclical Behavior of Real Wages Change Over Time?" *American Economic Review* 94 (4): 836–56.

Justiniano, A., G. E. Primiceri, and A. Tambalotti. 2010. "Investment Shocks and Business Cycles." *Journal of Monetary Economics* 57 (2): 132–45.

Katayama, M., and K. H. Kim. 2013. “The Delayed Effects of Monetary Shocks in a Two-Sector New Keynesian Model.” *Journal of Macroeconomics* 38 (Part B): 243–59.

Khan, A., and J. K. Thomas. 2014. “Revisiting the Tale of Two Interest Rates with Endogenous Asset Market Segmentation.” *Review of Economic Dynamics* 18 (2): 243–68.

Kim, J., and F. J. Ruge-Murcia. 2009. “How Much Inflation Is Necessary to Grease the Wheels?” *Journal of Monetary Economics* 56 (3): 365–77.

King, R. G., and M. W. Watson. 1998. “The Solution of Singular Linear Difference Systems under Rational Expectations.” *International Economic Review* 39 (4): 1015–26.

———. 2002. “System Reduction and Solution Algorithms for Singular Linear Difference Systems under Rational Expectations.” *Computational Economics* 20 (1–2): 57–86.

Klenow, P. J., and O. Kryvtsov. 2005. “State-Dependent or Time-Dependent Pricing: Does It Matter for Recent U.S. Inflation?” NBER Working Paper No. 11043.

———. 2008. “State-Dependent or Time-Dependent Pricing: Does It Matter for Recent U.S. Inflation?” *Quarterly Journal of Economics* 123 (3): 863–904.

Landry, A. 2009. “Expectations and Exchange Rate Dynamics: A State-Dependent Pricing Approach.” *Journal of International Economics* 78 (1): 60–71.

———. 2010. “State-Dependent Pricing, Local-Currency Pricing, and Exchange Rate Pass-Through.” *Journal of Economic Dynamics and Control* 34 (10): 1859–71.

Le Bihan, H., J. Montornes, and T. Heckel. 2012. “Sticky Wages: Evidence from Quarterly Microeconomic Data.” *American Economic Journal: Macroeconomics* 4 (3): 1–32.

Levin, A., V. Wieland, and J. C. Williams. 1998. “Robustness of Simple Monetary Policy Rules under Model Uncertainty.” FEDS Paper No. 45, Board of Governors of the Federal Reserve System.

Midrigan, V. 2011. “Menu Costs, Multiproduct Firms, and Aggregate Fluctuations.” *Econometrica* 79 (4): 1139–80.

Nakamura, E., and J. Steinsson. 2008. “Five Facts about Prices: A Reevaluation of Menu Cost Models.” *Quarterly Journal of Economics* 123 (4): 1415–64.

———. 2010. "Monetary Non-Neutrality in a Multi-Sector Menu Cost Model." *Quarterly Journal of Economics* 125 (3): 961–1013.

Nakov, A., and C. Thomas. 2014. "Optimal Monetary Policy with State-Dependent Pricing." *International Journal of Central Banking* 10 (3): 49–94.

Olivei, G., and S. Tenreyro. 2007. "The Timing of Monetary Policy Shocks." *American Economic Review* 97 (3): 636–63.

———. 2010. "Wage-Setting Patterns and Monetary Policy: International Evidence." *Journal of Monetary Economics* 57 (7): 785–802.

Smets, F., and R. Wouters. 2007. "Shocks and Frictions in US Business Cycles: A Bayesian DSGE Approach." *American Economic Review* 97 (3): 586–606.

Taylor, J. B. 1980. "Aggregate Dynamics and Staggered Contracts." *Journal of Political Economy* 88 (1): 1–23.

———. 1999. "Staggered Price and Wage Setting in Macroeconomics." In *Handbook of Macroeconomics*, Vol. 1B, ed. J. B. Taylor and M. Woodford, 1009–50 (chapter 15). Elsevier Science B.V.

Walque, G., M. Krause, S. Millard, J. Jimeno, H. L. Bihan, and F. Smets. 2010. "Some Macroeconomic and Monetary Policy Implications of New Micro Evidence on Wage Dynamics." *Journal of the European Economic Association* 8 (2–3): 506–13.

Walsh, C. E. 2010. *Monetary Theory and Policy*. MIT Press.