State Dependency in Price and Wage Setting*

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August 26, 2014

Abstract

There is some evidence that the timing and frequency of individual wage adjustments depend on economic conditions. This paper investigates aggregate implications of such state dependency in wage setting. I develop a New Keynesian model in which the timing and frequency of price and wage adjustments are endogenously determined in the presence of fixed costs for price and wage setting. I find that state dependency reduces the ability of nominal wage stickiness to generating short-run money nonneutralities. The increase in output following an expansionary monetary shock is smaller and less persistent under state- than time-dependent wage setting, which fixes the timing and frequency of adjustments at the steady state. Further, following an expansionary monetary shock, the real wage rises under state-dependent wage setting, while it falls under time-dependent setting. The response under state-dependent setting is consistent with that of the U.S. economy.

JEL classification: E31, E32.

Keywords: Nominal wage stickiness, state-dependent setting, money nonneutralities, New Keynesian models.

*I am grateful to Bill Dupor for his comments, encouragement, and guidance. I also would like to thank Michael Dotsey, Paul Evans, Yuko Imura, Aubhik Khan, Robert King, Nan Li, Virgiliu Midrigan, Masao Ogaki, Ricardo Reis, Takeki Sunakawa, Julia Thomas, Alexander Wolman, and participants at the Macro Lunch Workshop at Ohio State University, DSGE Workshop at Senshu, Macroeconomics Workshop at Kyoto, Eastern Economic Association Annual Conference 2011, and Midwest Economics Association Annual Meeting 2011, and Summer Workshop on Economic Theory 2014, for valuable comments and suggestions. Any remaining errors are my own.

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1 Introduction

Micro-level nominal wage adjustments have important effects on the aggregate economy. As Christiano, Eichenbaum, and Evans (2005) show, staggered wage setting is key to accounting for the empirical response of output and inflation to a monetary shock. Erceg, Henderson, and Levin (2000) show that staggered wage adjustments generate a welfare cost for strict price inflation targeting, which is optimal under flexible wages. Hence, nominal wage stickiness is relevant for business cycle fluctuations and optimal monetary policy.

Recent studies examine the aggregate implications of various features of wage setting. Olivei and Tenreyro (2007, 2010) find that the output response to a monetary shock differs across quarters in data and this difference can be explained by the difference in the frequency of wage changes across quarters. Dixon and Kara (2010, 2011) and Dixon and Le Bihan (2012) show that the heterogeneity in contract lengths observed in micro-level data helps accounting for the aggregate fluctuations in data, specifically, the persistent response of output and inflation to a monetary shock.

While these studies substantially deepen our understandings on how wage setting affects aggregate fluctuations, there is one feature that has not been investigated: state dependency in wage setting. In existing studies, wage adjustments follow the so-called time-dependent setting, such as Calvo (1983)- or Taylor (1980)-type setting, and the timing and frequency of wage adjustments are invariant to the aggregate state. However, there is some evidence for state dependency in wage setting, evidence that the timing and frequency of individual wage adjustments depend on economic states. 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."[1] Further, state-dependent setting has advantage over time-dependent setting for policy analysis because the timing and frequency of wage

[1] Barattieri, Basu, and Gottschalk (2010) analyze the Survey of Income and Program Participation in the U.S. and report the comovement of the quarterly frequency of wage changes with inflation. In contrast, Le Bihan, Montornes, and Heckel (2012) find no such relationship in France. One plausible explanation for the difference is that the labor market works differently in these two countries.

adjustments could change with policy. While Huang and Liu (2002) and Barattieri, Basu, and Gottschalk (2010) suggest that state dependency in wage setting is worth investing, to the best of my knowledge, no paper has actually examined it.

To fill the gap, this paper analyzes aggregate implications of state dependency in wage setting. Specifically, I compare the response to a monetary shock under state- and time-dependent wage setting in a New Keynesian model. The source of money nonneutralities has been one of the most important issues in macroeconomics, and time-dependent wage stickiness is known to generate sizeable money nonneutralities in New Keynesian setting (Huang and Liu (2002) and Christiano, Eichenbaum, and Evans (2005)). Recent studies also analyze various features of wage setting by examining a monetary shock in a New Keynesian model (Olivei and Tenreyro (2007, 2010), Dixon and Kara (2010, 2011) and Dixon and Le Bihan (2012)). The present paper follows the approach in the literature.

As the initial step to study state-dependent wage setting, this paper builds on the seminal state-dependent pricing model of Dotsey, King, and Wolman (1999) and develops a model with state dependency in both price and wage setting.[2] The price-setting side of the model is the same as that of Dotsey, King, and Wolman (1999). Price adjustments are staggered because price-setting fixed costs differ across firms. However, since all firms face the identical sequence of marginal costs, adjusting firms set the same new price, as in conventional time-dependent pricing models. Consequently, the price distribution, which is an endogenous state variable, is fully captured by the prices set in previous periods and the fraction of firms charging those prices. As for wage setting, this paper departs from Dotsey, King, and Wolman (1999), which assume a representative household and perfectly flexible wages. Specifically, in the present model, households supply differentiated labor services, and wage adjustments are staggered because households face different wage-setting fixed costs.[3] Since

[2]The Dotsey, King, and Wolman (1999) model is widely used for analyzing aggregate price dynamics. Bakhshi, Kahn, and Rudolf (2007) derive the New Keynesian Phillips curve for the model. Based on the model, Landry (2009, 2010) develop a two-country model with state-dependent pricing and analyze exchange rate movements. See also Dotsey and King (2005, 2006).

[3]Blanchard and Kiyotaki (1987) also assume wage-setting fixed costs. One interpretation of wage-setting costs is that in order to change wages, workers have to spend some time to negotiate with their employers

adjusting households set the same new wage under the assumptions commonly made for time-dependent setting models, the wage distribution is also explained by two factors: the wages set in previous periods and the fraction of households charging those wages. Therefore, the resulting model with state dependency in both price and wage setting can be solved using the method developed by Dotsey, King, and Wolman (1999).[4]

This paper finds that state dependency weakens the ability of nominal wage stickiness to generating short-run money nonneutralities. The increase in output following an expansionary monetary disturbance is smaller and less persistent under state- than time-dependent setting, in which the timing and frequency of wage adjustments are invariant to the shock. Further, state dependency generates the response of the real wage that is empirically more plausible than that under time-dependent setting. Under state-dependent setting, the real aggregate wage rises following an expansionary monetary shock, as consistent with the U.S. data (see Christiano, Eichenbaum, and Evans (2005)). In contrast, the real wage falls under time-dependent setting.

The impact of state dependency in wage setting is explained as follows. An expansionary monetary shock raises the aggregate price and increases consumption and labor hours. Hence, households have incentive to raise wages and reduce their labor hours. Since households can choose when to change wages under state-dependent setting, the fraction of households raising wages increases. In contrast, by assumption, the fraction does not increase under time-dependent setting. Crucially, state dependency also raises the wage set by adjusting households. Since state dependency increases the number of wage increases, the aggregate wage rises more substantially under state- than time-dependent setting. The higher aggregate wage under state-dependent setting has two opposing effects on the optimal resetting wage. First, adjusting households need to raise wages more substantially because

and outsource their homework, such as house cleaning, baby sitting, and so on.

[4] It is hard to solve a state-dependent pricing model because the price distribution is an endogenous state variable. The problem is worse here because the present model has two different distributions (prices and wages) that evolve independently. The present paper employs the structure of Dotsey, King, and Wolman (1999) and successfully solves the model with state dependency in both price and wage setting.

under monopolistic competition in the labor market, households' labor hours increase with the aggregate wage. Second, since firms raise prices more substantially and the increases in consumption and labor hours are mitigated, the optimal resetting wage becomes lower. Under reasonable parameter values and inflation rate, the relative wage effect dominates.[5] Hence, the resetting wage is higher under state- than time-dependent setting.

Since more households raise wages and those households also set a higher wage, the aggregate wage rises much more quickly under state- than time-dependent setting, leading to a faster aggregate price adjustment and a smaller and less persistent increase in output. Under the benchmark parameterization, which generates fluctuations in the frequency of wage changes that are in line with those estimated by Card and Hyslop (1997), the cumulative output response decreases by 50% as wage setting switches from time to state dependent.

The aggregate impact of state dependency in wage setting resembles the impact of state dependency in price setting. As in existing models, in the present model, state dependency in price setting reduces the increase in output that follows an expansionary monetary shock.[6] However, the impact is weaker than that of state-dependent wage setting. Although state dependency in price setting increases the fraction of firms raising prices, adjusting firms set a *lower* price under state- than time-dependent pricing, as in the Dotsey, King, and Wolman (1999) original model. Since state dependency increases the number of price increases, the aggregate price rises more substantially under state- than time-dependent pricing. Critically, because of the higher aggregate price, the increases in consumption and labor hours are mitigated, decreasing the nominal marginal cost (wage) under reasonable parameterization.

[5] This result generalizes the result of Huang and Liu (2002). Huang and Liu (2002) show that in a New Keynesian model, the response of optimal resetting wage can be decomposed into the response of the aggregate wage and that of output and under reasonable parameter values, the optimal wage rises with the aggregate wage more substantially than with output. Huang and Liu (2002) obtain this result under Taylor-type wage setting, flexible prices, and a zero steady-state inflation rate. The present paper shows that a similar result holds under state-dependent wage setting, state-dependent pricing, and a empirically relevant positive inflation rate.

[6] Golosov and Lucas (2007) find that money nonneutralities decrease substantially as price setting switches from time to state dependent. Midrigan (2011) proposes a model in which money nonneutralities are similar between state- and time-dependent pricing. Dotsey, King, and Wolman (1999), Dotsey and King (2005, 2006), Devereux and Siu (2007), Klenow and Kryvtsov (2008), and Nakamura and Steinsson (2010) also compare money nonneutralities under state- and time-dependent pricing.

Hence, the optimal price is lower under state- than time-dependent pricing, offsetting the impact of the increase in the number of price increases. As a result, the overall impact of state dependency is reduced. Under the benchmark parameterization, which generates fluctuations in the frequency of price changes that are comparable to those estimated by Nakamura and Steinsson (2008), the cumulative output response decreases only by 25% as price setting switches from time to state dependent.

The rest of this paper is organized as follows. Section 2 describes the model, while Section 3 explains the benchmark parameter values and the steady state. Section 4 compares the response to a monetary shock under state- and time-dependent setting for wage and price adjustments. Section 5 conducts robustness checks. Section 6 concludes.

2 Model

Consider a New Keynesian model. Firms face monopolistic competition in the goods market, produce differentiated goods, and set the nominal prices of their products. Since price adjustments incur fixed costs, firms infrequently change their prices. As in Dotsey, King, and Wolman (1999), price-setting costs differ across firms, making price adjustments staggered. Households face monopolistic competition in the labor market and supply differentiated labor services. I introduce staggered wage adjustments in a similar way to price setting: Households set the nominal wages for their labor services subject to fixed costs, which vary across households.

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

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

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

where $y_t(z)$ 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. Cost minimization implies that firms choose inputs so that

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

and

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

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. Note that the marginal cost is common for all firms.

Each firm sets the price of its product $P_t(z)$ and produces the quantity demanded at the price. The demand for each product is given by

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

where P_t is the aggregate price index, which is defined as

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

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

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

Firms infrequently change prices 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 both over time and across firms. Since firms face the identical marginal cost of production, the resetting price P_t^* is common to all adjusting firms, as under Calvo-type setting and as shown below.

Since adjusting firms set the same price, at the beginning of any given period, a fraction $\theta_{j,t}^p$ of firms charge $P_{t-j}^*, j = 1, ..., J$. The price distribution, including the number of price vintages J, is endogenously determined. Under positive inflation and bounded price-setting costs, firms eventually change prices, and J is finite.

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

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

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 adjusting firms is given by

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

$j = 1, ..., J-1$, and $\alpha_{J,t}^p = 1$. This is also the probability of price adjustments before firms draw a current price-setting cost. The fraction and probability of price changes increase with the value of adjusting prices.

The value of an adjusting firm is

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

where E_t is the conditional expectation and λ_t is households' marginal utility of consumption. The first term is the current profit. The rest is the present value of the expected next-period value. 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 present value of the expected next-period price-setting cost, and $\Xi^p_{j,t+1}$, $j = 1, ..., J$, is defined as

$$\Xi^p_{j,t+1} = \int_0^{\bar{\xi}^p_{j,t+1}} x g^p(x) dx, \quad (9)$$

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 nonadjusting firm is

$$v^p_{j,t} = [(\frac{P^*_{t-j}}{P_t})^{1-\epsilon^p} - mc_t(\frac{P^*_{t-j}}{P_t})^{-\epsilon^p}]c_t \quad (10)$$
$$+\beta E_t \frac{\lambda_{t+1}}{\lambda_t}[(1-\alpha^p_{j+1,t+1})v^p_{j+1,t+1} + \alpha^p_{j+1,t+1}v^p_{0,t+1} - w_{t+1}\Xi^p_{j+1,t+1}],$$

$j = 1, ..., J-2$, and

$$v^p_{J-1,t} = [(\frac{P^*_{t-(J-1)}}{P_t})^{1-\epsilon^p} - mc_t(\frac{P^*_{t-(J-1)}}{P_t})^{-\epsilon^p}]c_t + \beta E_t \frac{\lambda_{t+1}}{\lambda_t}[v^p_{0,t+1} - w_{t+1}\Xi^p_{J,t+1}]. \quad (11)$$

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

$$[(1-\epsilon^p)\frac{1}{P_t}(\frac{P_t^*}{P_t})^{-\epsilon^p}c_t+\epsilon^p\frac{mc_t}{P_t}(\frac{P_t^*}{P_t})^{-\epsilon^p-1}c_t]+\beta E_t\frac{\lambda_{t+1}}{\lambda_t}(1-\alpha^p_{1,t+1})\frac{\partial v^p_{1,t+1}}{\partial P_t^*}=0. \tag{12}$$

Replacing the terms $\partial v^p_{j,t+j}/\partial P_t^*, j=1,...,J-1$, using (10) and (11) yields

$$P_t^*=\frac{\epsilon^p}{\epsilon^p-1}\frac{E_t\sum_{j=0}^{J-1}\beta^j\left(\frac{\omega^p_{j,t+j}}{\omega^p_{0,t}}\right)\left(\frac{\lambda_{t+j}}{\lambda_t}\right)P_{t+j}^{\epsilon^p-1}c_{t+j}P_{t+j}mc_{t+j}}{E_t\sum_{j=0}^{J-1}\beta^j\left(\frac{\omega^p_{j,t+j}}{\omega^p_{0,t}}\right)\left(\frac{\lambda_{t+j}}{\lambda_t}\right)P_{t+j}^{\epsilon^p-1}c_{t+j}}, \tag{13}$$

where $\omega^p_{j,t+j}/\omega^p_{0,t}=(1-\alpha^p_{j,t+j})(1-\alpha^p_{j-1,t+j-1})\cdots(1-\alpha^p_{1,t+1}), j=1,...,J-1$, is the probability of keeping P_t^* until $t+j$. In contrast to Calvo-type setting, the probability endogenously evolves as the probability of price adjustments changes (see (8)). However, as under Calvo-type setting, 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, indexed by $h\in[0,1]$, supplies a differentiated labor service. A household's preference is

$$E_t\sum_{l=0}^{\infty}\beta^l[\frac{c_{t+l}(h)^{1-\sigma}}{1-\sigma}-\chi n_{t+l}(h)^{\zeta}], \tag{14}$$

where $c_t(h)$ 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 at the wage rate. 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. Cost minimization by the labor aggregator implies the demand for each labor service:

$$n_t(h) = (\frac{W_t(h)}{W_t})^{-\epsilon^w} n_t, \tag{15}$$

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

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

and n_t is the demand for the composite labor. The composite labor is defined as

$$n_t = [\int_0^1 n_t(h)^{\frac{\epsilon^w - 1}{\epsilon^w}} dh]^{\frac{\epsilon^w}{\epsilon^w - 1}}. \tag{17}$$

Households infrequently adjust wages 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 contingent bonds, implying that a household faces the budget constraint:

$$\frac{W_t(h)n_t(h)}{P_t} + \frac{M_{t-1}(h) + B_{t-1}(h) + D_t(h)}{P_t} = c_t(h) + \frac{\delta_{t+1,t} B_t(h)}{P_t} + \frac{M_t(h)}{P_t} + \frac{W_t}{P_t} \xi_t^w(h), \tag{18}$$

where $M_t(h)$ is the household's money holding, $\delta_{t+1,t}$ is the vector of the prices of contingent claims, $B_t(h)$ is the vector of those claims purchased, $B_{t-1}(h)$ is the quantity of the claims given the current state of nature, and $D_t(h)$ is nominal profits paid by firms to households. 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: $\lambda_t(h) = \lambda_t$. Consequently, the optimal wage W_t^* is common to all adjusting households, as in Calvo-type setting and as shown below.

Since adjusting households set the same wage, at the start of any given period, a fraction

$\theta^w_{q,t}$ of households charge $W^*_{t-q}, q = 1, ..., Q$. The wage distribution, including the number of wage vintages Q, is endogenously determined. Under positive inflation and bounded wage-setting costs, households eventually change wages, and Q is finite.

Let $v^w_{0,t}$ denote the utility of a household (relating to wage-setting decisions) that resets its wage in the current period and $v^w_{q,t}, q = 1, ..., Q-1$, denote the utility of a household that keeps its wage unchanged at W^*_{t-q}. No household keeps its wage at W^*_{t-Q}. Households change wages if

$$v^w_{0,t} - v^w_{q,t} \geq w_t \lambda_t \xi^w_t. \tag{19}$$

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

$$\alpha^w_{q,t} = G^w(\frac{v^w_{0,t} - v^w_{q,t}}{w_t \lambda_t}), \tag{20}$$

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

The utility of a household adjusting its wage is

$$\begin{aligned} v^w_{0,t} \quad = \quad & \max_{W^*_t}\{[\lambda_t \frac{W^*_t}{P_t}(\frac{W_t(h)}{W_t})^{-\epsilon^w} n_t - \chi(\frac{W_t(h)}{W_t})^{-\epsilon^w \xi} n^{\xi}_t] \\ & + \beta E_t[(1-\alpha^w_{1,t+1})v^w_{1,t+1} + \alpha^w_{1,t+1} v^w_{0,t+1} - \lambda_{t+1} w_{t+1} \Xi^w_{1,t+1}]\}. \end{aligned} \tag{21}$$

The first term is the current utility. The rest is the present value of the expected next-period utility. With probability $(1-\alpha^w_{1,t+1})$, the household keeps W^*_t in the next period. With probability $\alpha^w_{1,t+1}$, 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 $\Xi^w_{q,t+1}, q = 1, ..., Q$, is defined as

$$\Xi^w_{q,t+1} = \int_0^{\bar{\xi}^w_{q,t+1}} x g^w(x) dx, \tag{22}$$

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 nonadjusting household is

$$\begin{aligned} v^w_{q,t} &= [\lambda_t \frac{W^*_{t-q}}{P_t}(\frac{W^*_{t-q}}{W_t})^{-\epsilon^w} n_t - \chi(\frac{W^*_{t-q}}{W_t})^{-\epsilon^w \zeta} n_t^{\zeta}] \\ &\quad +\beta E_t[(1-\alpha^w_{q+1,t+1})v^w_{q+1,t+1} + \alpha^w_{q+1,t+1} v^w_{0,t+1} - \lambda_{t+1} w_{t+1} \Xi^w_{q+1,t+1}], \end{aligned} \tag{23}$$

$q = 1, ..., Q-2$, and

$$v^w_{Q-1,t} = [\lambda_t \frac{W^*_{t-(Q-1)}}{P_t}(\frac{W^*_{t-(Q-1)}}{W_t})^{-\epsilon^w} n_t - \chi(\frac{W^*_{t-(Q-1)}}{W_t})^{-\epsilon^w \zeta} n_t^{\zeta}] + \beta E_t[v^w_{0,t+1} - \lambda_{t+1} w_{t+1} \Xi^w_{Q,t+1}]. \tag{24}$$

The optimal wage W^*_t satisfies the first-order condition for (21):

$$\begin{aligned} &\frac{\lambda_t}{P_t}(\frac{W^*_t}{W_t})^{-\epsilon^w} n_t - \epsilon^w \lambda_t \frac{W^*_t}{P_t}(\frac{W^*_t}{W_t})^{-\epsilon^w - 1} \frac{n_t}{W_t} + \epsilon^w \chi \zeta (\frac{W^*_t}{W_t})^{-\epsilon^w \zeta - 1} \frac{n_t^{\zeta}}{W_t} \\ &+\beta E_t (1-\alpha^w_{1,t+1}) \frac{\partial v^w_{1,t+1}}{\partial W^*_t} = 0. \end{aligned} \tag{25}$$

Replacing the terms $\partial v^w_{q,t+q} / \partial W^*_t$, $q = 1, ..., Q-1$, using (23) and (24), (25) can be written as

$$E_t \sum_{q=0}^{Q-1} \beta^q (\frac{\omega^w_{q,t+q}}{\omega^w_{0,t}}) \left\{ \frac{\epsilon^w - 1}{\epsilon^w} \frac{W^*_t}{P_{t+q}} \lambda_{t+q} - \chi \zeta [(\frac{W^*_t}{W_{t+q}})^{-\epsilon^w} n_{t+q}]^{\zeta - 1} \right\} (\frac{W^*_t}{W_{t+q}})^{-\epsilon^w} n_{t+q} = 0, \tag{26}$$

where $\omega^w_{q,t+q}/\omega^w_{0,t} = (1-\alpha^w_{q,t+q})(1-\alpha^w_{q-1,t+q+1})...(1-\alpha^w_{1,t+1}), q = 1, ..., Q-1,$ denote the probability of keeping W^*_t until $t+q$. The probability endogenously varies over time, as indicated by (20). However, as under Calvo-type 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 and Supply

Money demand is given by the conventional money demand function:

$$\ln \frac{M_t}{P_t} = \ln c_t - \eta R_t, \tag{27}$$

where M_t is the quantity of money and R_t is the nominal interest rate, which is defined by

$$\frac{1}{1+R_t} = \beta E_t[\frac{\lambda_{t+1}}{\lambda_t}\frac{P_t}{P_{t+1}}].$$

The growth rate of money ($\mu_t = M_t/M_{t-1}$) follows a simple money supply rule:

$$\ln \mu_t = (1-\rho)\ln \bar{\mu} + \rho \ln \mu_{t-1} + \epsilon_t, \tag{28}$$

where $\bar{\mu}$ is the steady-state growth rate of money and equals the steady-state inflation rate $\bar{\Pi}$, whereas ϵ_t is an independently and identically distributed mean-zero shock.

3 Parameter Values and the Steady State

This section explains parameter values and the steady state.

3.1 Parameter Values

Table 1 lists the benchmark parameter values. The values are similar to those used in previous studies, such as Erceg, Henderson, and Levin (2000). The length of a period is one quarter. The annual real interest rate is 4% and $\beta = 0.99$. The relative risk aversion σ is 1.5, whereas the exponent of labor ζ is 1.5, implying a Frisch labor supply elasticity of 2.0. The disutility of labor χ is 4.39, implying that the composite labor supplied at the steady state n^{ss} is 30% of the total time endowment (normalized to one). The labor share is $\alpha = 0.7$. The elasticity of demand for differentiated goods and labor services are $\epsilon^p = \epsilon^w = 4.33$, generating 30% markup rates under flexible prices and wages. The interest semi-elasticity of money demand η is 0.[8] The amount of money grows by 3% annually at the steady state, so the quarterly steady-state money growth and inflation rates are $\bar{\mu} = \bar{\Pi} = 1.03^{0.25}$. The persistence in money growth ρ is 0.5.[9]

As in Dotsey, King, and Wolman (1999), the following distributional family is assumed for price-setting costs:

$$\xi^p(x) = B^p \frac{\arctan(b^p x - d^p \pi) + \arctan(d^p \pi)}{\arctan(b^p - d^p \pi) + \arctan(d^p \pi)}, \tag{29}$$

where $x \in [0, 1]$ and ξ^p is the inverse of G^p. As for the shape of the benchmark distribution, I set $b^p = 16$ and $d^p = 2$, assuming a similar shape to that in Dotsey, King, and Wolman (1999) and Bakhshi, Kahn, and Rudolf (2007). As Figure 1 shows, a large fraction of firms draw either small or large price-setting costs. As shown in Section 4.3, this distribution generates the comovement of the quarterly frequency of price changes with inflation that is in line with the comovement of the *monthly* frequency of price changes with inflation in the U.S. documented by Nakamura and Steinsson (2008). The maximum cost is then chosen targeting the average price duration of 3.0 quarters at the steady state ($B^p = 0.0020$). The degree of price stickiness is similar to that observed in the U.S. under the inflation rate close to the level assumed here.[10] The implied price-setting cost is small, and at the steady state,

[8] As in Dotsey, King, and Wolman (1999), I solved the present model with the interest elasticity of money demand of –0.5 ($\eta = 50.74$). The main result did not change.

[9] This value is largely consistent with the U.S. data. Mankiw and Reis (2002), Chari, Kehoe, and McGrattan (2000), and Midrigan (2011) use $\rho = 0.5$, 0.57, and 0.61, respectively.

[10] Nakamura and Steinsson (2008) find that the mean (median) price duration is about 11–13 (8–11) months for 1988–2005 in the U.S. Bils and Klenow (2004) report a median duration of 5.5 months for 1995–1997 in the U.S. The average CPI inflation rate was around 3% during the sample periods of these two studies.

0.03% of total labor is used for price adjustments.

The same distributional family is assumed for wage-setting costs:

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

where $x \in [0,1]$ and ξ^w is the inverse of G^w. There is no concrete evidence on fluctuations in the *quarterly* frequency of wage changes for the U.S. economy.[11] Hence, I assume the same shape as that for price-setting costs ($b^w = 16$ and $d^w = 2$). However, as shown in Section 4.3, the implied fluctuations in the *annual* frequency of wage changes are in line with those estimated by Card and Hyslop (1997). The maximum cost B^w is 0.0097, targeting the average wage spell of 3.8 quarters at the steady state. The degree of wage stickiness is in the range of the estimates by Barattieri, Basu, and Gottschalk (2014).[12] The implied wage-setting cost is small, and 0.07% of total labor is used for wage adjustments at the steady state.

3.2 Steady State

I find the steady state by solving nonlinear equations for equilibrium conditions. The number of price vintages J and the number of wage vintages Q are endogenously determined at this stage, so that all the firms in the Jth price vintage change their prices and all the households in the Qth wage vintage reset their wages.

Table 2 shows the steady-state adjustment patterns. At the steady state, 32.9% of prices are adjusted in any given quarter. The frequency of price changes is comparable to the monthly frequency of price changes of 9–12% reported by Nakamura and Steinsson (2008). In the present model, the probabilities of price adjustments α_j^p are increasing in price vintages because under positive inflation, the benefits of adjustments are larger for older vintages. In

[11] Barattieri, Basu, and Gottschalk (2010) provide evidence that the quarterly frequency of wage changes is positively correlated with CPI inflation.

[12] Barattieri, Basu, and Gottschalk (2014) find that the average wage duration of 3.8–4.7 quarters in the U.S. if a constant hazard function is assumed.

contrast, Nakamura and Steinsson (2008) show that the hazard function for price changes is nearly flat in the U.S. As shown in Section 5, the main conclusion of this paper is robust even when the distribution of price-setting cost is chosen to produce a constant hazard function, although the resulting model generates fluctuations in the frequency of price changes that are much smaller than those reported by Nakamura and Steinsson (2008).

As for wage adjustments, at the steady state, 26.6% of wages are adjusted in any given quarter. The frequency of wage changes is in line with 21.1–26.6% of quarterly frequency of wage adjustments estimated by Barattieri, Basu, and Gottschalk (2014). In the present model, the probabilities of wage adjustments α_q^w are increasing in wage vintages as under positive inflation, the benefits of adjustments are larger for older vintages. In contrast, Barattieri, Basu, and Gottschalk (2014) show that the hazard for wage changes is increasing up to one year and then is decreasing in the U.S.

4 Impulse Responses to Monetary Shocks

This section analyzes the impact of state dependency in price and wage setting on short-run aggregate fluctuations and compare impulse responses to a monetary shock under state- and time-dependent setting.[13] State- and time-dependent setting have the identical steady state shown in the last section, but they respond to monetary disturbances in different ways. Under state-dependent setting, firms and households optimally change the timing of adjustments in response to monetary shocks. Hence, there are endogenous movements in the probabilities (frequency) of price and wage adjustments and the fractions of prices and wages in vintages. In contrast, under time-dependent setting, firms and households cannot change when to adjust and must follow the steady-state timing. Therefore, the probabilities (frequency) of adjustments and fractions of prices and wages in vintages remain at their steady-state counterparts.

[13] 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 on their websites.

In what follows, I consider all the possible combinations of price and wage setting regimes: 1) state-dependent price setting and state-dependent wage setting (SS); 2) state-dependent price setting and time-dependent wage setting (ST); 3) time-dependent price setting and state-dependent wage setting (TS); and 4) time-dependent price setting and time-dependent wage setting (TT).

I examine impulse responses to an expansionary monetary shock ϵ_t of 0.05%.[14] Specifically, the quantity of money increases by 0.05% in period 1 relative to the steady state with 3% annual inflation and then gradually converges to 0.1% above the level that reaches without the shock. Figure 2 presents the responses of output, the aggregate price, the aggregate wage, and the real wage (the ratio of the aggregate wage to the aggregate price). In the following subsections, I first compare the responses under state- and time-dependent wage setting and then conduct a similar comparison for price adjustments.

4.1 Impact of State Dependency in Wage Setting

Under state-dependent wage setting, an expansionary monetary shock leads to a temporal increase in output and a persistent rise in the aggregate price, as in existing New Keynesian models with nominal wage stickiness. However, state dependency in wage setting dampens the increase in output. As an example, compare state- and time-dependent wage setting under state-dependent pricing (SS versus ST).[15] The cumulative increase in output for ten quarters after the shock is about 50% lower under SS (0.074%) than ST (0.152%). In contrast, the aggregate price and wage rise more quickly under SS than ST. Further, the real wage rises under SS as consistent with empirical evidence, while it decreases under ST.

Next, in order to understand the above results, I examine how state dependency influences micro-level wage adjustments. When the expansionary monetary shock occurs, the aggregate price rises, lowering households' real wages. Further, both consumption and labor hours

[14] 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, changing the numbers of price and wage vintages. I analyze a small shock to avoid this problem.

[15] The same pattern is observed under time-dependent pricing (TS versus TT).

increase, raising households' marginal rate of substitution of leisure for consumption. Hence, households have incentive to raise wages and reduce their labor hours. Since all adjusting households choose the same wage in the present model, micro-level wage adjustments are largely described by the fraction of households raising wages and the wage chosen by those households.

The right two panels of Figure 3 present the responses of these two dimensions of wage adjustments to the monetary shock. Since households can change when to adjust wages, the fraction of adjusting households increases under state-dependent setting. For example, under SS, the fraction of wage increases rises by 0.74 of a percentage point in period 1 when the shock occurs. In contrast, by construction, the fraction does not increase under time-dependent setting (ST). Importantly, adjusting households also set a higher wage under state- than time-dependent setting. The rise in the resetting wage is 0.075% under SS, whereas it is 0.069% under ST. Hence, in the present model, state dependency increases not only the number of wage increases, but also the size of each wage increase.

Why does state dependency in wage setting raise the resetting wage? State dependency increases the number of wage increases, and hence the aggregate wage rises more substantially under state- than time-dependent setting. The higher aggregate wage has two opposing effects on the optimal resetting wage, as indicated by (26). On one hand, adjusting households must raise wages more substantially in order to reduce labor hours because their hours increase with the aggregate wage, as shown in (15). On the other hand, since firms raise their prices more substantially in response to the higher nominal marginal cost (wage), the increases in consumption and aggregate labor hours are reduced, lowering the optimal wage. Log-linearizing (26) suggests that under parameter values commonly used in the literature, the relative wage effect dominates.[16] Hence, the optimal resetting wage is higher under state- than time-dependent wage setting.

Crucially, state dependency has a persistent effect. As a result of the increase in the

[16] The analysis also shows that changes in the probability of keeping the wage have a only minor impact on the change in the resetting wage.

fraction and size of wage increases in the initial period, the aggregate wage in the following periods is higher under state- than time-dependent setting. Because of the relative wage effect, the fraction of wage increases is higher and adjusting households raise wages more substantially under state- than time-dependent setting in the subsequent periods. In response, firms raise prices more quickly under state- than time-dependent wage setting, leading to a faster rise in the aggregate price and a smaller and less persistent increase in output. Since the aggregate wage rises more quickly than the aggregate price, the real wage rises under state-dependent setting. In contrast, the real wage falls under time-dependent setting.

4.2 Impact of State Dependency in Price Setting

State dependency in price setting also reduces the increase in output following an expansionary monetary shock, while quickening aggregate price and wage adjustments. However, in the present model, the impact is smaller than that of state dependency in wage setting. For example, compare state- and time-dependent price setting under state-dependent wage setting (SS versus TS). The cumulative increase in output for ten quarters after the shock is only 25% lower under SS (0.074%) than under TS (0.099%)

The left panels of Figure 3 show how state dependency in price setting affects micro-level price adjustments. Since firms can optimally change the timing of price adjustments under state-dependent pricing, the monetary shock increases the fraction of price increases. For example, under SS, the fraction rises by 0.7 percentage points in the first period. In contrast, by construction, the fraction does not increase under time-dependent pricing (TS). However, adjusting firms set a *lower* price under state- than time-dependent pricing. The resetting price rises by 0.069% under TS, but only by 0.058% under SS.

Why does state dependency in price setting lower the resetting price? As shown in Dotsey, King, and Wolman (1999), linearizing (13) indicates that the response of the resetting price is mostly driven by the movement of the nominal marginal cost and other factors are less relevant. State-dependent pricing increases the number of price increases, raising the aggregate price. However, the higher aggregate price reduces the increases in consumption and aggregate labor, suppressing the rise in the marginal cost (wage). The latter effect dominates under plausible parameter values, and the nominal marginal cost rises less substantially under state- than time-dependent pricing. Hence, adjusting firms raise prices less substantially under state- than time-dependent setting.

To summarize, state dependency in price setting increases the fraction of price increases, but *decreases* the size of price increases following an expansionary monetary shock. Hence, it has a smaller impact on short-run money nonneutralities than state dependency in wage setting, which increases both number and size of wage increases.

4.3 Changes in the Frequency of Wage Adjustments

A crucial question is whether the present model predicts empirically plausible fluctuations in the frequency of wage changes. According to the data reported in Card and Hyslop (1997), a 0.1 percentage point increase in an annual CPI inflation rate is associated with a 0.24 percentage point increase in the *annual* frequency of wage increases and a 0.1 percentage point decline in the *annual* frequency of wage decreases. To calculate similar statistics for the model, consider one year that ends in period 1 when the expansionary monetary shock occurs. In the year, because of the shock, an annual inflation rate rises by 0.03 percentage point relative to the steady state, while the annual frequency of wage increases rises by 0.06 percentage point. The effect of the shock on the annual frequency of wage increases peaks in the year that ends in period 5. An inflation rate rises by 0.07 percentage point, while the frequency of wage increases rises by a 0.52 percentage point. Hence, the model predicts that a 0.1 percentage point rise in CPI inflation is associated with a 0.20–0.76 percentage point rise in the annual frequency of wage increases, with the two-year average of 0.40 percentage point. Although the model's result is conditional on monetary shocks, it is not at least inconsistent with the empirical relationship between inflation and the frequency of wage increases. Further, since the model omits reductions in wage decreases, it is likely to understate the reduction in money nonneutralities caused by state dependency in wage setting.

5 Robustness Checks

[*to be written*]

6 Conclusion

[*to be written*]

Table 1: Parameter values

Parameter	Description	Value
β	discount factor	0.99
σ	relative risk aversion	1.5
ζ	exponent on labor	1.5
χ	disutility of labor	4.39
α	labor's share	0.7
ϵ^p	elasticity of demand for differentiated goods	4.33
ϵ^w	elasticity of demand for differentiated labor services	4.33
η	interest semi-elasticity of money demand	0
$\bar{\mu}$ ($\bar{\Pi}$)	steady-state money growth (inflation)	$1.03^{0.25}$
ρ	persistence in money growth	0.5
(B^p, b^p, d^p)	distribution of price-setting costs	$(0.0020, 16, 2)$
(B^w, b^w, d^w)	distribution of wage-setting costs	$(0.0097, 16, 2)$

Note: This table lists benchmark parameter values. One period in the model corresponds to one quarter.

Table 2: Steady state

A: Fractions of prices and wages

Vintage (j/q)	Price (θ_j^p)	Wage (θ_q^w)
1	32.86%	26.55%
2	26.82%	23.80%
3	18.44%	18.28%
4	11.61%	12.68%
5	6.80%	8.24%
6	3.47%	5.09%
7	–	2.99%
8	–	1.63%
9	–	0.72%

B: Probabilities of price and wage adjustments

Vintage (j/q)	Price (α_j^p)	Wage (α_q^w)
1	0.184	0.104
2	0.312	0.232
3	0.370	0.306
4	0.414	0.350
5	0.489	0.382
6	1	0.412
7	–	0.456
8	–	0.559
9	–	1

Note: Panel A shows the fractions of prices (firms) and wages (households) in each vintage at the beginning of a period. Panel B presents the hazard functions for prices and wages.

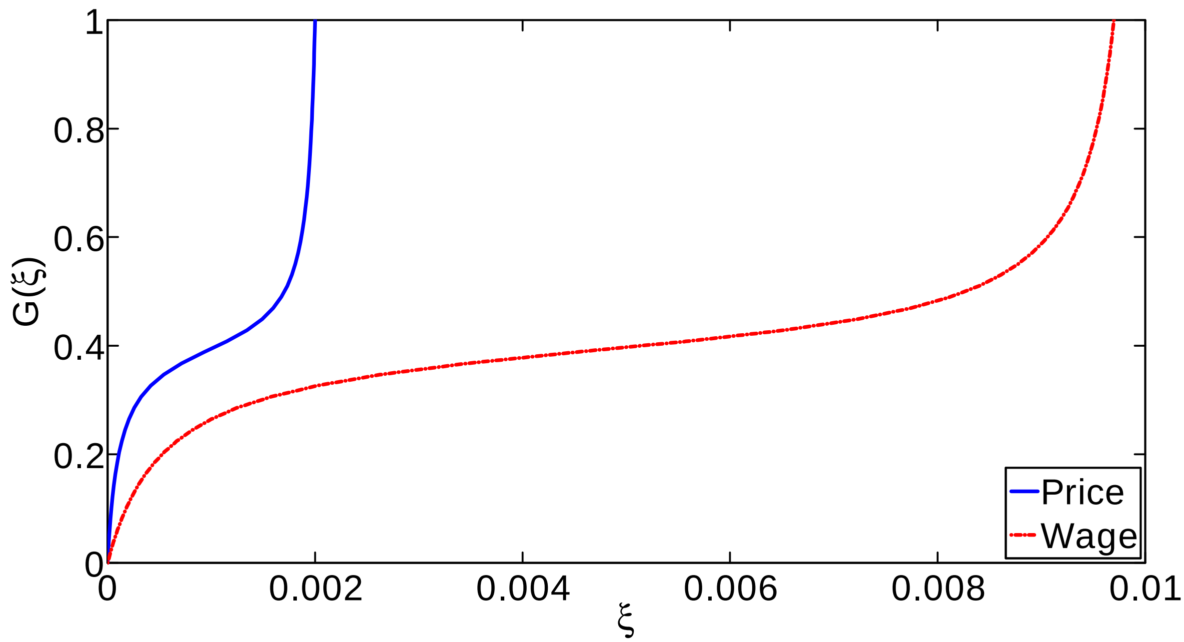

Figure 1: Price- and wage-setting costs

Note: This figure plots the cumulative distribution functions of price- and wage-setting costs.

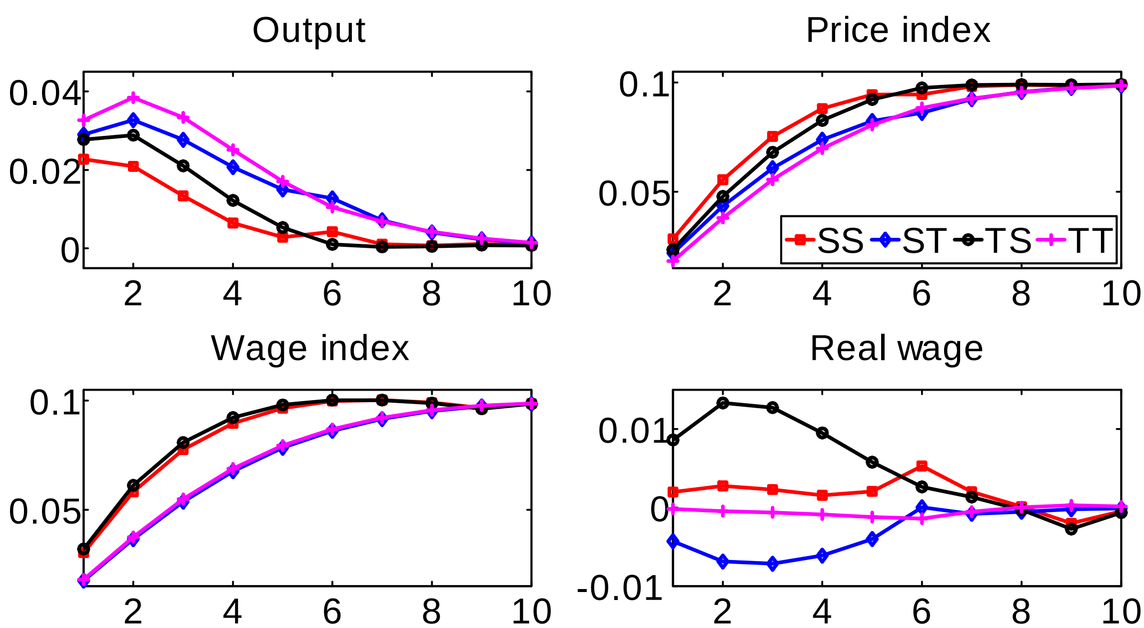

Figure 2: Shock to money growth rate

Note: This figure shows the impulse responses to a money growth shock of 0.05% that occurs in period 1. The horizontal axis shows quarters, while the vertical axis is the percent deviation from the steady state. The following four cases are compared: 1) state-dependent price setting and state-dependent wage setting (SS); 2) state-dependent price setting and time-dependent wage setting (ST); 3) time-dependent price setting and state-dependent wage setting (TS); and 4) time-dependent price setting and time-dependent wage setting (TT).

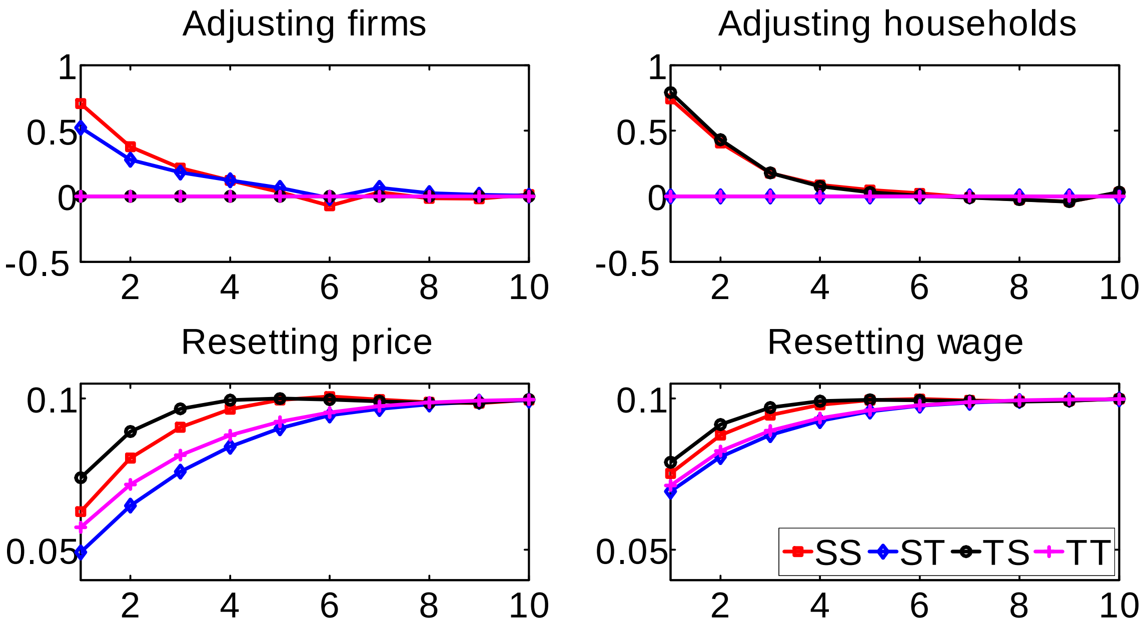

Figure 3: Micro-level price and wage adjustments

Note: This figure shows the impulse responses to a money growth shock of 0.05% that occurs in period 1. The horizontal axis shows quarters. For adjusting firms and households, the vertical axis is the percentage point deviation from the steady state. For the target price and wage, it is the percent deviation from the steady state. The following four cases are compared: 1) state-dependent price setting and state-dependent wage setting (SS); 2) state-dependent price setting and time-dependent wage setting (ST); 3) time-dependent price setting and state-dependent wage setting (TS); and 4) time-dependent price setting and time-dependent wage setting (TT).

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