# Monetary Policy Implications of State-Dependent Prices and Wages

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Philadelphia, January 2018

# Motivation

1. Nominal rigidity of some form is a key feature of most monetary models
   - Common frameworks: Calvo (1983), Rotemberg (1982), Taylor (1979)
2. Golosov-Lucas (2007): *"state dependent"* (SD) model based on menu cost implies monetary shocks have trivial real effects
   - The reason is endogenous *"selection"*: the most misaligned prices get reoptimized, so the price level is more flexible than a Calvo model implies
3. But newer SD pricing models deliver substantial money non-neutrality, closer to Calvo
   - The reason is a weaker selection effect: Midrigan (2011), Alvarez et al. (2011), Matejka (2011), Costain and Nakov (2011, 2015)
4. These new models match better retail price microdata, and respond well to big changes in the environment, e.g. VAT shocks (Karadi and Reiff 2016)

# Motivation

9. Unlike applied DSGEs, studies of state-dependent pricing mostly ignore all other frictions: *sticky prices only*

10. Takahashi (2017) is the only existing analysis of the interaction between SD sticky prices and SD sticky wages
    - Takahashi ignores idiosyncratic shocks, so cannot match histograms of price or wage changes (the usual targets of the newer SD models)

11. In this paper we compare model to price adjustment data and wage adjustment data simultaneously

12. We evaluate the role of both rigidities, simultaneously, for monetary policy

13. Huang and Liu (2002) suggest that wage stickiness is more important than price stickiness for money non-neutrality

# This paper

1. Studies *state dependent prices and wages* simultaneously
2. Nominal rigidities following "Logit Price Dynamics" (Costain-Nakov, 2015)
   - Main assumption: precise decisions are costly
3. Game theoretic approach: "control costs"
   - Postulate a cost function for precision
   - Implies mistakes occur in equilibrium
   - If precision is measured by entropy, then choices distributed as logit
4. Market structure following Erceg, Henderson, and Levin (2000)
   - Firms are monopolistic suppliers of goods, subject to a Calvo friction
   - Workers are monopolistic suppliers of labor, subject to a Calvo friction
5. This paper: Erceg-Henderson-Levin (2000) meets Costain-Nakov (2015)

# Model: monopolistic firms

- **Profits**:
  - Firm $i$'s demand: $Y_{it} = Y_t P_t^{\epsilon} P_{it}^{-\epsilon}$
  - Firm $i$'s output: $Y_{it} = A_{it} N_{it}$, where $\log A_{it}$ is AR(1)
  - Profits: $U_t(P_{it}, A_{it}) \equiv P_{it} Y_{it} - W_t N_{it}$

- **Control variables**:
  - Firm adjusts its price $P_{it}$
  - Current $P_{it}$ remains in effect until firm sets a new price $P'$
  - Output and labor are demand driven.

- **Frictions**:
  - Adjustment itself is costless (zero menu costs)
  - But greater precision requires more decision time, so decisions are costly

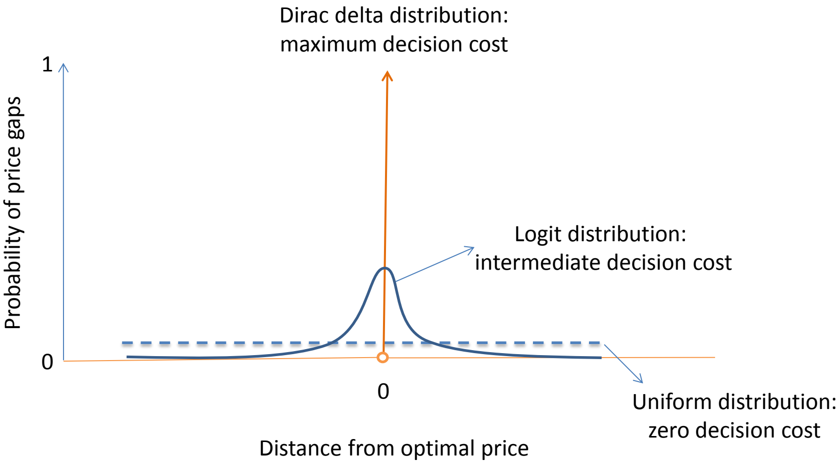
# Costs of decision-making: price choice

- Think of decisions as probability distributions over alternatives.
- Assume precision is costly.
- Let $\pi(p)$ be a firm's chosen distribution over its log real price $p$.

*Assumption 1. The time cost $\tau$ of decision $\pi$ is:*

$$\kappa_\pi \mathcal{D}(\pi || \eta) \equiv \kappa_\pi \int \pi(p) \ln \left( \frac{\pi(p)}{\eta(p)} \right) dp$$

*where $\eta(p)$ is an exogenous "default" decision distribution.*


Dirac delta distribution:
maximum decision cost
1
Probability of price gaps
Logit distribution:
intermediate decision cost
0
0
Uniform distribution:
zero decision cost
Distance from optimal price

# Costs of decision-making: timing choice

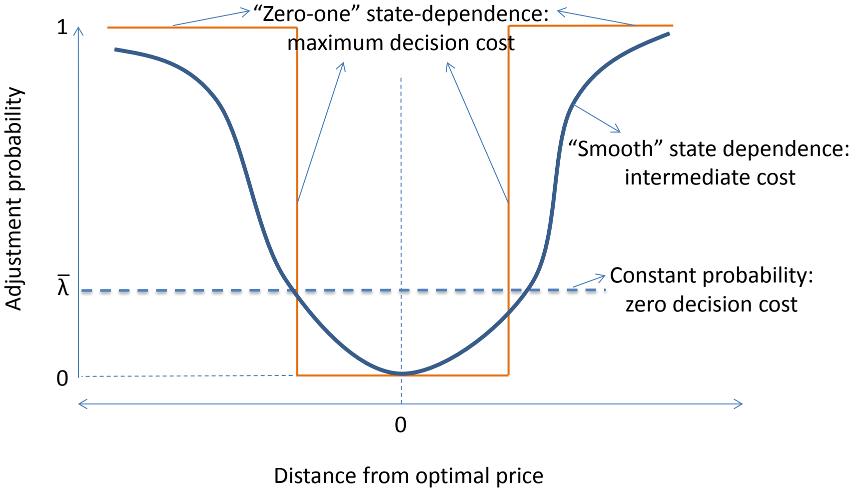
- Let $\lambda$ be the probability of making a decision in the current period.

*Assumption 2. The time cost $\mu$ of choosing whether or not to make a decision is:*

$$\kappa_\lambda \mathcal{D}\left((\lambda, 1-\lambda)||(\bar{\lambda}, 1-\bar{\lambda})\right) \equiv \kappa_\lambda \left(\lambda \log \frac{\lambda}{\bar{\lambda}} + (1-\lambda) \log \frac{1-\lambda}{1-\bar{\lambda}}\right)$$

*where $\bar{\lambda}$ is an exogenous "default" probability.*

# Repricing probability



# Bellman equations (real)

- Real value of producing at current firm-specific state $(p, a)$:

$$v_t(p,a) = u_t(p,a) + \max_{\lambda}\left[(1-\lambda)v_t^e(p,a) + \lambda\tilde{v}_t(a) - w_t\kappa_\lambda\mathcal{D}\left((\lambda, 1-\lambda)||(\bar{\lambda}, 1-\bar{\lambda})\right)\right]$$

  - Where $\tilde{v}_t(a)$ is the firm's expected value, conditional on adjustment:

$$\tilde{v}_t(a) = \max_{\pi(\tilde{p})}\int \pi(\tilde{p})v_t^e(\tilde{p},a)d\tilde{p} - w_t\kappa_\pi\mathcal{D}(\pi||\eta)$$
$$\text{s.t.} \quad \int \pi(\tilde{p})d\tilde{p} = 1$$

  - And $v_t^e(p,a)$ is the expected value, conditional on unchanged nominal price:

$$v_t^e(p,a) = E_t\left\{q_{t,t+1}v_{t+1}(p - i_{t+1}, a')|a\right\}$$

# Distribution of actions

- Both price distribution and probability of decision are weighted logits:
- Distribution of prices, conditional on decision:

$$\pi_t(p|a) = \frac{\eta(p)\exp\left(\frac{v_t^e(p,a)}{\kappa_\pi w_t}\right)}{\int \eta(\tilde{p})\exp\left(\frac{v_t^e(\tilde{p},a)}{\kappa_\pi w_t}\right) d\tilde{p}}$$

- Probability of making a decision:

$$\lambda_t(p,a) = \frac{\bar{\lambda}}{\bar{\lambda} + (1-\bar{\lambda})\exp\left(\frac{-d_t(p,a)}{\kappa_\lambda w_t}\right)},$$

- Where $d_t(p,a)$ is the real loss from inaction:

$$d_t(p,a) = \tilde{v}_t(a) - v_t^e(p,a)$$

# Adding wage stickiness in an analogous way

- Next, do **wage stickiness too**
  - Model wages and prices analogously, as in **Erceg-Henderson-Levin (2000)**
  - We assume each worker sells a distinct type of labor in a monopolistically competitive fashion to many firms
  - So we are not yet addressing any other labor market frictions
  - No search and matching, no unemployment
- Study **effects of monetary shocks** in a control cost model, assuming:
  - Sticky prices and wages
  - Sticky prices, flexible wages
  - Flexible prices, sticky wages
  - Flexible prices and wages
- And compare results to Calvo model

# Model: monopolistic supply of labor

- Firm $j$'s labor input is an aggregate of differentiated labor types $i$:

$$N_{jt} = \left\{ \int_0^1 N_{ijt}^{\frac{\epsilon_n - 1}{\epsilon_n}} di \right\}^{\frac{\epsilon_n}{\epsilon_n - 1}}$$

- Worker $i$'s effective labor $N_{ijt}$ is the product of labor time $H_{ijt}$ and worker-specific productivity $Z_{it}$:

$$N_{ijt} = Z_{it} H_{ijt}, \quad \text{where} \;\; \log Z_{it} \text{ is AR(1)}$$

- Let $W_{it}$ be worker $i$'s wage per unit of time,
- The aggregate wage index $W_t$ is:

$$W_t = \left\{ \int_0^1 \left( \frac{W_{it}}{Z_{it}} \right)^{1-\epsilon_n} di \right\}^{\frac{1}{1-\epsilon_n}}.$$

# Model: monopolistic supply of labor

- Demand for labor time of worker *i* is:

$$H_{it} \; = \; H_t(W_{it}, Z_{it}) \; \equiv \; Z_{it}^{\epsilon_n - 1} N_t W_t^{\epsilon_n} W_{it}^{-\epsilon_n}.$$

- Households' utility is:

$$u(C_t) - X(H_t + \mu_t^w + \tau_t^w) + \nu(M_t/P_t)$$

where $\mu_t^w$ and $\tau_t^w$ are time devoted to wage decisions

- Then the marginal value of time is

$$\xi_t \; \equiv \; \frac{P_t}{u'(C_t)} X'(H_t + \mu_t^w + \tau_t^w)$$

# Costs of decision-making

- Let $\pi^w(w)$ be a worker's chosen distribution over its log real wage $w$.
- Let $\rho$ be the probability of making a decision in the current period.

*Assumption 3. The time cost $\tau^w$ of decision $\pi^w$ is:*

$$\kappa_w \mathcal{D}(\pi^w || \eta^w) \equiv \kappa_w \int \pi^w(w) \ln\left(\frac{\pi^w(w)}{\eta^w(w)}\right) dw$$

*where $\eta^w(w)$ is an exogenous "default" decision.*

*Assumption 4. The time cost $\mu^w$ of choosing whether to make a decision is:*

$$\kappa_w \mathcal{D}\left((\rho, 1-\rho)||(\bar{\rho}, 1-\bar{\rho})\right) \equiv \kappa_w \left(\rho \log \frac{\rho}{\bar{\rho}} + (1-\rho)\log \frac{1-\rho}{1-\bar{\rho}}\right)$$

*where $\bar{\rho}$ is an exogenous "default" probability.*

# Bellman equation (real)

$$
\begin{aligned}
I_t(w,z) \;&= \max_{\tau^w,\mu^w,\rho,\pi^w(\tilde{w})} e^w h_t(w,z) - \frac{X(h_t(w,z)+\tau^w+\mu^w)}{u'(C_t)} \\
&\quad + (1-\rho) I_t^e(w,z) + \rho \int \pi^w(\tilde{w}) I_t^e(\tilde{w},z) d\tilde{w} \\
\text{s.t.} \quad & \int \pi^w(\tilde{w}) d\tilde{w} = 1, \\
& \rho\kappa_w \int \pi^w(\tilde{w}) \ln\left(\frac{\pi^w(\tilde{w})}{\eta^w(\tilde{w})}\right) d\tilde{w} \;=\; \tau^w, \\
& \kappa_\rho \left[\rho \ln\left(\frac{\rho}{\bar{\rho}}\right) + (1-\rho)\ln\left(\frac{1-\rho}{1-\bar{\rho}}\right)\right] \;=\; \mu^w.
\end{aligned}
$$

# Distribution of actions

- Both wage distribution and probability of decision are weighted logits:
- Distribution of wages, conditional on decision:

$$\pi_t^w(w|z) = \frac{\eta^w(w)\exp\left(\frac{l_t^e(w,z)}{\kappa_w \xi_t}\right)}{\int \eta^w(w')\exp\left(\frac{l_t^e(w',z)}{\kappa_w \xi_t}\right) dw'}$$

- Probability of making a decision:

$$\rho_t(w,z) = \frac{\bar{\rho}}{\bar{\rho} + (1-\bar{\rho})\exp\left(\frac{-d_t^w(w,z)}{\kappa_\rho \xi_t}\right)},$$

- Where $d_t^w(w,z)$ is the real loss from inaction:

$$d_t^w(w,z) = \tilde{l}_t(z) - l_t^e(w,z)$$

RESULTS:

LINEAR LABOR DISUTILITY

$$X(h) = \chi h$$

# Common parameters (same in all specifications)

| | | |
|---|---|---|
| Discount factor | $\beta^{-12} = 1.04$ | Golosov-Lucas (2007) |
| CRRA | $\gamma = 2$ | Ibid. |
| Labor supply | $\chi = 6$ | Ibid. |
| MIUF coeff. | $\nu = 1$ | Ibid. |
| Elast. subst. | $\epsilon = 7$ | Ibid. |
| Money growth | $\mu^{12} = 1.02$ | Dominick's dataset: 2% annual inflation |
| *Shocks to firms* | | |
| Persistence prod. | $\rho = 0.95$ | Blundell-Bond (2000) |
| Std. dev. prod. | $\sigma = 0.06$ | Eichenbaum et. al. (2009) |
| *Shocks to workers* | | |
| Persistence prod. | $\rho = 0.95$ | Same as firms |
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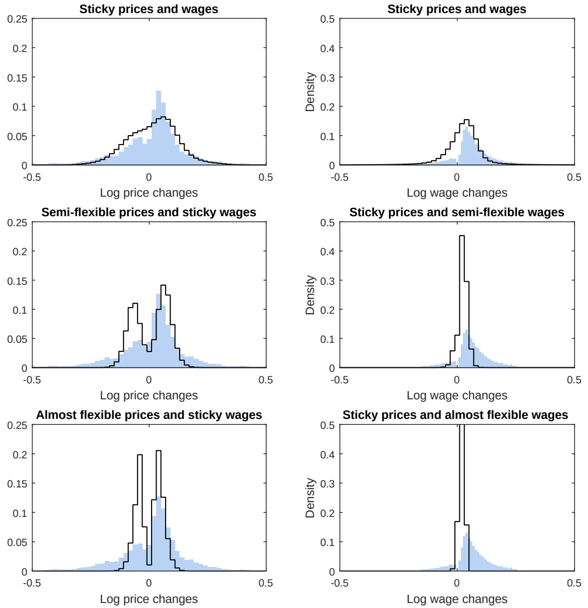
# Versions compared

- We compare six calibrations of the model:
  - **V1: Benchmark. Sticky prices and wages:** $\kappa_\pi = \kappa_\lambda = \kappa_w = \kappa_\rho = 0.017^*$
  - V2: Semi-flexible prices and sticky wages: $\kappa_\pi = \kappa_\lambda = 0.0017$
  - V3: Flexible prices and sticky wages: $\kappa_\pi = \kappa_\lambda = 0.00017$
  - V4: Sticky prices and semi-flexible wages: $\kappa_w = \kappa_\rho = 0.0017$
  - V5: Sticky prices and flexible wages: $\kappa_w = \kappa_\rho = 0.00017$
  - V6: Flexible prices and flexible wages: $\kappa_\pi = \kappa_\lambda = \kappa_w = \kappa_\rho = 0.00017$

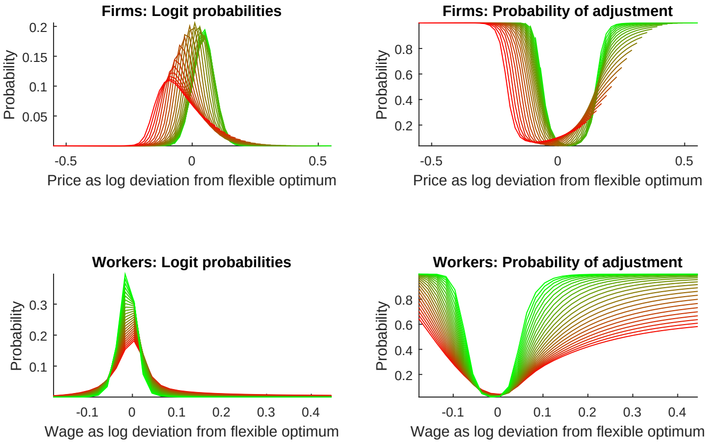
  * *Note*: This is the estimate of the benchmark model in "Logit price dynamics".

- We will also compare each version to a Calvo model with sticky prices and wages with the same frequency of adjustment.

# Nonzero price and wage changes: varying decision cost



# Price and wage setting: sticky prices and wages (V1)



# Steady-state behavior and decision costs

| | V1<br>Both sticky | V3<br>Fl-$P$, St-$W$ | V5<br>St-$P$, Fl-$W$ | V6<br>Both flex. |
|---|---|---|---|---|
| Frequency and size of adjustments (%): | | | | |
| Price adj. freq. | 10.1 | 54.4 | 10.4 | 54.4 |
| Wage adj. freq. | 6.02 | 6.04 | 7.28 | 6.95 |
| Abs($\Delta \ln p$) | 8.57 | 4.76 | 8.57 | 4.76 |
| Abs($\Delta \ln w$) | 6.14 | 6.16 | 1.98 | 2.29 |
| Costs as % of revenues: | | | | |
| Price setting costs | 0.51 | 0.07 | 0.51 | 0.07 |
| Price timing costs | 0.37 | 0.03 | 0.37 | 0.03 |
| Loss w.r.t. full rationality | 1.78 | 0.13 | 1.78 | 0.13 |
| Wage setting costs | 0.13 | 0.14 | 0.004 | 0.004 |
| Wage timing costs | 0.14 | 0.15 | 0.004 | 0.003 |
| Loss w.r.t. full rationality | 1.62 | 1.71 | 1.18 | 1.17 |

*Note*: Firms' costs stated as percentage of average revenue.

Workers' costs stated as percentage of average labor income.

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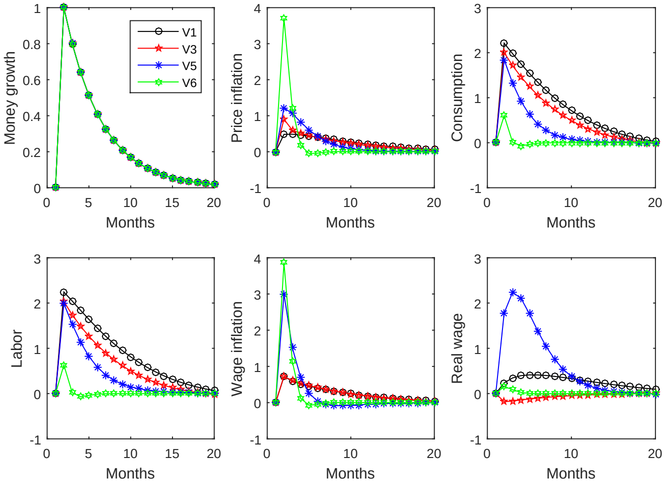
# Money supply shock: effects of price and wage stickiness

**V1: sticky, V3: Pflex/Wsticky, V5: Psticky/Wflex, V6: flexible**



# Money supply shock: effects of stickiness (Calvo model)

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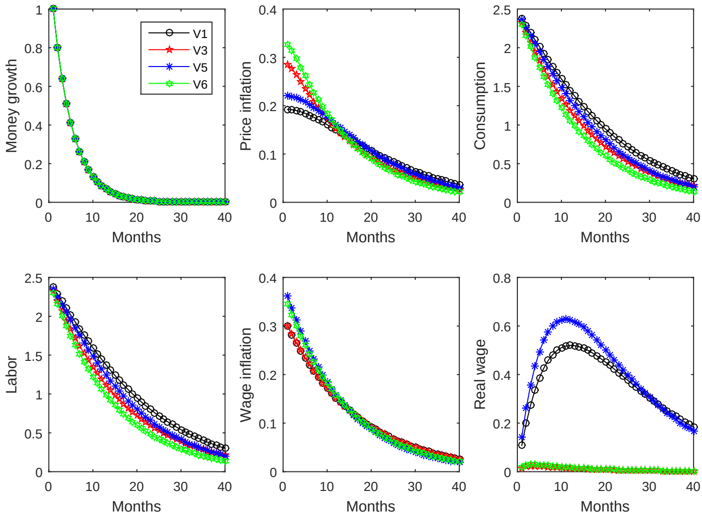


# Main findings: linear case

1. Decreased decision costs for $P$ or $W$ have the expected effects:
   - Make adjustment more frequent
   - Make average adjustment smaller
   - Decrease time devoted to the decision

2. **Sticky wages generate more nonneutrality** than sticky prices
   - If $W$ is flexible, stimulative effect of money supply increase is offset by $\frac{W}{P} \uparrow$
   - Model with sticky wages and flexible prices generates most of the nonneutrality observed in the model in which both are sticky

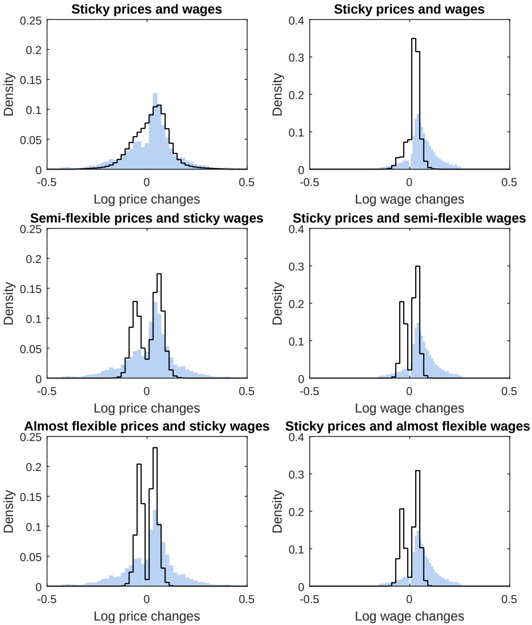
3. Control costs on $P$ and $W$ recovers **roughly half of the nonneutrality** observed in an analogous Calvo model

# RESULTS:

# CONVEX LABOR DISUTILITY

$$X(h) = \frac{\chi}{1+\zeta} h^{1+\zeta}, \quad \zeta = 0.5$$

# Nonzero price and wage changes: varying decision cost



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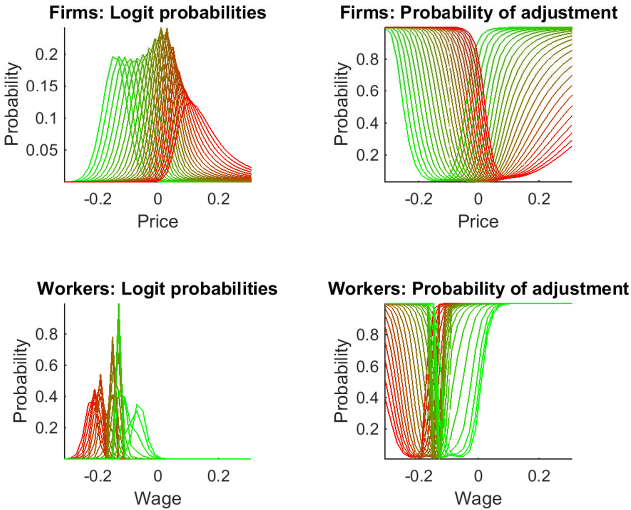

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|---|---|---|---|---|
| Frequency and size of adjustments (%): | | | | |
| Price adj. freq. | 7.74 | 49.6 | 7.78 | 50.4 |
| Wage adj. freq. | 7.44 | 8.34 | 22.1 | 22.0 |
| Abs($\Delta \ln p$) | 7.30 | 4.02 | 7.24 | 3.99 |
| Abs($\Delta \ln w$) | 3.26 | 2.85 | 3.85 | 3.85 |
| | | | | |
| Costs as % of revenues: | | | | |
| Price setting costs | 0.49 | 0.07 | 0.47 | 0.06 |
| Price timing costs | 0.41 | 0.03 | 0.40 | 0.03 |
| Loss w.r.t. full rationality | 1.87 | 0.51 | 1.83 | 0.51 |
| | | | | |
| Wage setting costs | 0.96 | 1.18 | 0.03 | 0.03 |
| Wage timing costs | 0.67 | 0.77 | 0.01 | 0.01 |
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|---|---|---|---|---|
| Frequency and size of adjustments (%): | | | | |
| Price adj. freq. | 7.74 | 49.6 | 7.78 | 50.4 |
| Wage adj. freq. | 7.44 | 8.34 | 22.1 | 22.0 |
| Abs($\Delta \ln p$) | 7.30 | 4.02 | 7.24 | 3.99 |
| Abs($\Delta \ln w$) | 3.26 | 2.85 | 3.85 | 3.85 |
| Costs as % of revenues: | | | | |
| Price setting costs | 0.49 | 0.07 | 0.47 | 0.06 |
| Price timing costs | 0.41 | 0.03 | 0.40 | 0.03 |
| Loss w.r.t. full rationality | 1.87 | 0.51 | 1.83 | 0.51 |
| Wage setting costs | 0.96 | 1.18 | 0.03 | 0.03 |
| Wage timing costs | 0.67 | 0.77 | 0.01 | 0.01 |
| Loss w.r.t. full rationality | 4.07 | 4.51 | 1.13 | 1.13 |

*Note*: Firms' costs stated as percentage of average revenue.

Workers' costs stated as percentage of average labor income.

# Steady-state behavior and decision costs

| | V1N Both sticky | V3N Fl-$P$, St-$W$ | V5N St-$P$, Fl-$W$ | V6N Both flex. |
|---|---|---|---|---|
| Frequency and size of adjustments (%): | | | | |
| Price adj. freq. | 7.74 | 49.6 | 7.78 | 50.4 |
| Wage adj. freq. | 7.44 | 8.34 | 22.1 | 22.0 |
| Abs($\Delta \ln p$) | 7.30 | 4.02 | 7.24 | 3.99 |
| Abs($\Delta \ln w$) | 3.26 | 2.85 | 3.85 | 3.85 |
| Costs as % of revenues: | | | | |
| Price setting costs | 0.49 | 0.07 | 0.47 | 0.06 |
| Price timing costs | 0.41 | 0.03 | 0.40 | 0.03 |
| Loss w.r.t. full rationality | 1.87 | 0.51 | 1.83 | 0.51 |
| Wage setting costs | 0.96 | 1.18 | 0.03 | 0.03 |
| Wage timing costs | 0.67 | 0.77 | 0.01 | 0.01 |
| Loss w.r.t. full rationality | 4.07 | 4.51 | 1.13 | 1.13 |

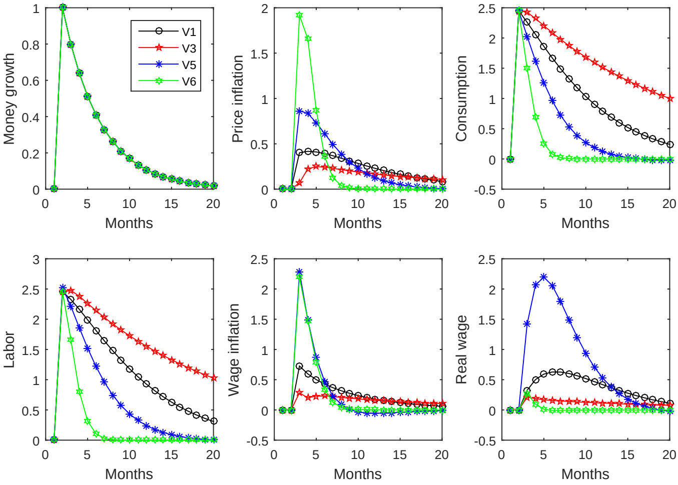
*Note*: Firms' costs stated as percentage of average revenue.

Workers' costs stated as percentage of average labor income.

# Money supply shock: effects of price and wage stickiness

## V1: sticky, V3: Pflex/Wsticky, V5: Psticky/Wflex, V6: flexible

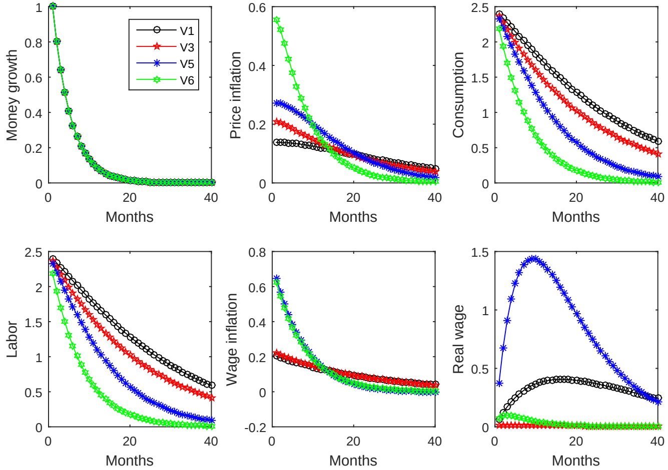
Figure 8: Money growth shock: effects of nominal rigidity. Error-prone pricing, $\zeta = 0.5$.



# Money supply shock: effects of stickiness (Calvo model)

**V1: sticky, V3: Pflex/Wsticky, V5: Psticky/Wflex, V6: flexible**

Figure 9: Money growth shock: effects of nominal rigidity. Calvo pricing, $\zeta = 0.5$.



# Conclusions

1. We study a DSGE model with SD prices and SD wages
2. Combines monopolistic competition in goods and labor inputs, following Erceg, Henderson, and Levin (2000), with nominal rigidity derived from costly decision-making, following Costain and Nakov (2015)
3. First paper to study state dependence in prices and wages in a model with idiosyncratic shocks, for comparison to microdata
4. We find that wage stickiness is more likely to cause persistent effects of monetary shocks than price stickiness
5. Huang and Liu (2002) reported the same finding for a time-dependent model; we are the first to study this issue in a state-dependent model
6. With nonlinear labor disutility, decreasing price stickiness, in the presence of sufficient wage stickiness, increases persistence of real effects of money shocks