Estimating Strategic Complementarity in a State-Dependent Pricing Model

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Macro Motivation

- Monetary policy effects depend on
  - the extent of price rigidity
  - the type of friction:
    - adjustment cost $\longrightarrow$ state dependency $\longrightarrow$ little effect
    - information cost $\longrightarrow$ time dependency $\longrightarrow$ stronger effect
  - price complementarity: how a desired price depends on other prices
    - strong strategic complementarity in price $\longrightarrow$ stronger monetary policy effect
      - when a price changes with most other prices fixed, it will change less.

Motivation: micro-macro conundrum

- Micro evidence seems consistent with
  - relatively high frequency of adjustments (Bils and Klenow 2004)
  - state-dependency (Nakamura and Steinson 2008, Klenow and Kritsov 2008, Gagnon 2009)

- Degree of strategic complementarity seems crucial to make it compatible with evidence that shocks (in particular monetary shocks) have important macro effects: Gertler and Leahy (2008).

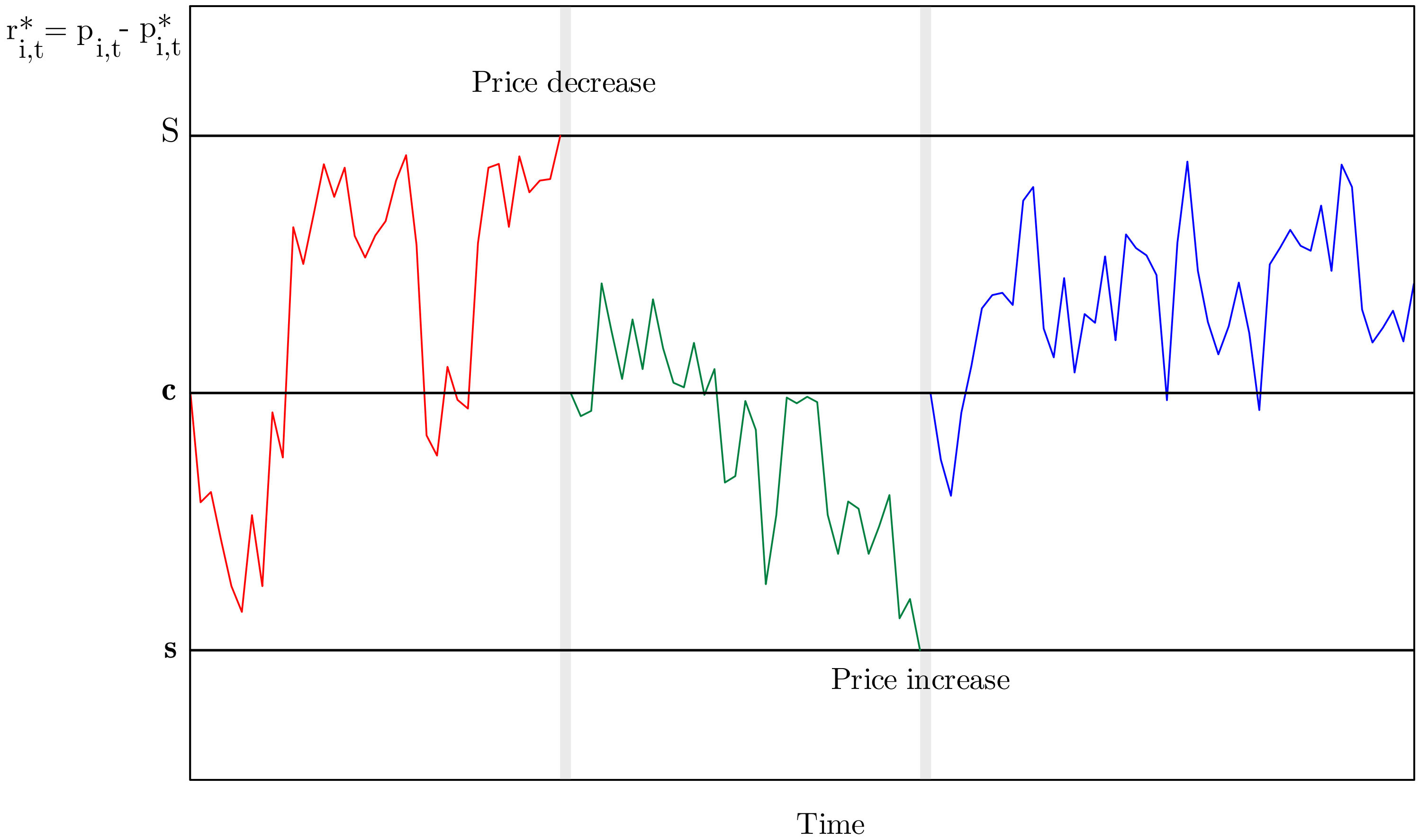
- Indirect evidence from micro data based on model simulation:
  - investigate whether specific channels are consistent with micro data:
  - low degree or no strategic complementarity:
    - Klenow and Willis (2006) - real rigidities through demand side a la Kimball (1995), large relative price variation in BLS,
    - Burstein and Hellwig (2007) - prices and market shares from scanner data of a large grocery chain,
    - Krivtsov and Midrigan (2010) - inventory dynamics inconsistent with marginal cost rigidity.

This paper: what we do

- Revisit the issue: what degree of strategic complementarity is consistent with micro data?

- Direct estimation of strategic complementarity parameter in the frictionless price equation from ocurrence of price adjustments:
  - Individual price adjustment data from Brazilian CPI of Getulio Vargas Foundation
    - large amount of macroeconomic variation in Brazilian sample.

$$p^*_{i,t} = \kappa + \zeta p_t + \boldsymbol{x}'_t \boldsymbol{\beta} + \tilde{\xi}_t + \tilde{a}_{i,t}$$



This paper 2:- what we do

- Price changes reflect frictionless optimal price variation but also the frequency of price adjustments. We disentangle those two effects by assuming firms follow a two-sided Ss rule (modeling selection):
  - adjustments are triggered whenever the price discrepancy attains a certain threshold.
  - it allows us to relate the price discrepancy (and conditional probability of adjusment) to the change in the frictionless optimal price since the last adjustment date.
  - assumptions for non-observable idiosyncractic and aggregate shocks $\longrightarrow$ a relation between probability of adjustments and the conditional mean of changes in the frictionless optimal price since the last adjustment

- With base on these assumptions and methodology we also:
  - recover the individual frictionless optimal price
  - estimate the parameters of the pricing rule.

This paper: how we do

- Not based on closed model simulation
  - The relations of the supply side of the economy are estimated without closing the model (Euler equation, monetary policy):
    - results should be robust to different specifications of the missing part.
- We are agnostic with respect to the specific mechanism generating strategic complementarity

Main results 1

- The parameter ζ ranges from 0.03 to 0.10, implying a high degree of strategic complementarity.

- This should lead to significant real effects of monetary shock:

  - As suggested by Gertler and Leahy's state-dependent model results with $\zeta = 0.08$.

Related literature

- Related to Bils, Klenon and Mahlin (2009, 2011) who aim at isolating price rigidity from strategic complementarity with the following measures:
  - theoretical reset price: the price the price-setter would choose if she could adjust.
  - empirical reset price (different because of selection): assumes that reset price inflation for non-adjusters is equal to the one for adjusters.
  - Compare empirical reset price measure of complete simulated models to the data.
- Under Ss rules, frictionless price inflation=theoretical reset price inflation
- Empirical reset price inflation reflects movements in the frictionless optimal price blurred by the selection effect.

Results 2

- We recover the frictionless optimal price:
  - Frictionless price inflation less persistent than inflation and more persistent than reset price inflation and slightly less persistent than inflation ($\rho_\pi = 0.51 > \rho_{\pi^*} = 0.21 > .\rho_{\widehat{\pi}^*} = -0.35$).
  - Frictionless price inflation has variability similar to inflation and much lower than reset price inflation. ($\sigma_{\widehat{\pi}^*} = 2.30\% > \sigma_{\pi^*} = 0.76\% \simeq \sigma_\pi = 0.72\%$)
  - IRF of frictionless optimal price similar to BKM's (2009) theoretical reset price inflation for state-dependent model with strategic complementarity.

Outline

- Model
- Empirical model and estimation
- Data
- Results
  - Strategic complementarity
  - Pricing rules
  - Actual, frictionless and reset inflation
- Conclusion

Model

- Illustrative model to derive frictionless optimal price equation. Several alternative specifications lead to the same equation.

- **Households**: the representative household seeks to maximize

$$\mathbb{E}_0 \left\{ \sum_{t=0}^{\infty} \beta^t \left[U_t \frac{C_t^{1-\sigma^{-1}}}{1-\sigma^{-1}} - \int_0^1 \frac{V_{i,t} L_{i,t}^{1+\delta}}{1+\delta} di \right] \right\},$$

where

$$C_t = \left[\int_0^1 C_{i,t}^{(\theta-1)/\theta} di \right]^{\theta/\theta-1}. \tag{1}$$

  – Demand for individual product:

$$C_{i,t} = C_t \left(\frac{P_{i,t}}{P_t} \right)^{-\theta}, \tag{2}$$

– Labor supply:

$$\frac{V_{i,t} L_{i,t}^{\delta}}{U_t C_t^{-\frac{1}{\sigma}}} = \frac{W_{i,t}}{P_t} \tag{3}$$

- **Firms**: Continuum of monopolistically competitive firms supplying differentiated goods.

  – Production function for firm i:

$$Y_{i,t} = A_{i,t} L_{i,t}^{\alpha} M_t^{(1-\alpha)}, \tag{4}$$

M_t - foreign input

  – Exogenous real exchange rate - E_t.

  – Segmented labor market (as in Woodford 2003)

Model 2

- – Assume for simplicity that exports and imports are equal. Equilibrium: $Y_t = C_t$

  – Real marginal cost function:

$$\psi(Y_{i,t}, Y_t, E_t; V_{i,t}, U_t, A_{i,t}) =$$
$$\overline{\kappa} A_{i,t}^{-\frac{1+\delta}{1+\delta(1-\alpha)}} Y_{it}^{\frac{\alpha\delta}{1+\delta(1-\alpha)}} Y_t^{\frac{\alpha\sigma^{-1}}{(1+\delta(1-\alpha))}} E_t^{\frac{(1-\alpha)+\delta(1-\alpha)}{1+\delta(1-\alpha)}} V_{i,t}^{\frac{\alpha}{1+\delta(1-\alpha)}} U_t^{-\frac{\alpha}{1+\delta(1-\alpha)}} \tag{5}$$

where

$$\overline{\kappa} \equiv \lambda \left[\frac{(1-\alpha)}{\alpha} \right]^{\frac{\alpha^2\delta(1-\alpha)}{1+\delta(1-\alpha)}}$$

Model 3: Frictionless optimal price

- **Frictionless optimal price**: Firms maximize profits subject to demand and cost yielding:

$$\frac{P_{i,t}^{*}}{P_t} = \mu\psi(Y_{i,t}, Y_t, E_t; V_{i,t}, U_t, A_{i,t}), \tag{6}$$

where $\mu \equiv \theta/(\theta - 1)$

  - Substituting the marginal cost expression (5) into the markup rule (6) and taking the log of the resulting expression yields:

$$p_{i,t}^{*} = \kappa + (1 - \zeta)\, p_t + \zeta \mathcal{Y}_t + \phi e_t + \tilde{\xi}_t + \tilde{a}_{i,t} \tag{7}$$

where

$$
\begin{aligned}
\zeta &\equiv \frac{\alpha\left(\delta+\sigma^{-1}\right)}{1+\delta\left[(1-\alpha)+\alpha\theta\right]} \\
\phi &\equiv \frac{(1+\delta)(1-\alpha)}{1+\delta(1-\alpha)+\theta\delta\alpha} \\
\tilde{a}_{i,t} &\equiv -\frac{1+\delta}{1+\delta(1-\alpha)+\theta\delta\alpha}a_{i,t}+\frac{\alpha}{1+\delta(1-\alpha)+\theta\delta\alpha}v_{i,t} \\
\tilde{\xi}_t &\equiv -\frac{\alpha}{1+\delta(1-\alpha)+\theta\delta\alpha}u_t \\
\kappa &\equiv \frac{1+\delta(1-\alpha)}{1+\delta(1-\alpha)+\theta\delta\alpha}\log\overline{\kappa}.
\end{aligned}
$$

Model 3: Frictionless optimal price

- When $\zeta < 1$, strategic complementarities in price setting.

- The degree of strategic complementarity depends:

  – positively on σ (elasticity of intertemporal substitution)

  – negatively on α (elasticity of product with respect to labor), and θ (elasticity of substitution among alternative varieties).

  – assuming $\sigma^{-1} \geq 1$, as usual in the literature, positively on δ (the inverse of the Frish elasticity of labor supply)

- Different mapping depending on details of structural model: homogenous labor markets leads to

$$\zeta = \frac{\alpha\left(\delta + \sigma^{-1}\right)}{1 + \delta\left(1 - \alpha\right)}$$

Model 4: Price rigidity model

- We want to estimate 7, but observe infrequent price changes.
- To bridge the gap: a state-dependent model of price rigidity.
- We assume firms follow Ss pricing rules parametrized by (s, c, S) - just postulated, but can be rationalized
  - state variable: price discrepancy
  $$r^*_{i,t} \equiv p_{i,t} - p^*_{i,t}.$$
  - adjustment rule:

$$\begin{cases} c - s & if \quad r^*_{it} \leq s \\ 0 & if \quad s \leq r^*_{it} \leq S \\ -(S - c) & if \quad r^*_{it} \geq S \end{cases} \tag{8}$$

Empirical model

$$\begin{aligned} r^*_{i,t} &\equiv p_{i,t} - p^*_{i,t} \\ &= p_{i,\tau_{i,t}} - p^*_{i,t} \\ &= c + p^*_{i,\tau_{i,t}} - p^*_{i,t}, \end{aligned} \tag{9}$$

- Rewrite p^*_{it} as:

$$p^*_{i,t} = \kappa + \boldsymbol{x}'_t\boldsymbol{\beta} + \tilde{\xi}_t + \tilde{a}_{i,t}$$

- Substituting our model for p^*_{it}:

$$\begin{aligned} r^*_{i,t} &= c + \left(\kappa + \boldsymbol{x}'_{\tau_{i,t}}\boldsymbol{\beta} + \tilde{\xi}_{\tau_{i,t}} + \tilde{a}_{i,\tau_{i,t}}\right) - \left(\kappa + \boldsymbol{x}'_t\boldsymbol{\beta} + \tilde{\xi}_t + \tilde{a}_{i,t}\right) \\ &= c + \left(\boldsymbol{x}_{\tau_{i,t}} - \boldsymbol{x}_t\right)'\boldsymbol{\beta} + \left(\tilde{\xi}_{\tau_{i,t}} - \tilde{\xi}_t\right) + \left(\tilde{a}_{i,\tau_{i,t}} - \tilde{a}_{i,t}\right) \\ &= c - \boldsymbol{z}'_{i,t}\boldsymbol{\beta} - \left(\tilde{\xi}_t - \tilde{\xi}_{\tau_{i,t}}\right) - \left(\tilde{a}_{i,t} - \tilde{a}_{i,\tau_{i,t}}\right) \end{aligned} \tag{10}$$

- $\boldsymbol{z}_{i,t} \equiv (x_t - x_\tau)$ is not the same for all firms as τ depends on both i and t.

Empirical model 2: specification of shocks

- **Aggregate shock**:

$$\tilde{\xi}_t = \tilde{\xi}_{t-1} + v_t, \quad v_t \sim \mathsf{IID}(0, \sigma_v^2). \tag{11}$$

- **Idiosyncratic shock**:

$$\tilde{a}_{i,t} = a_i + a_{i,t}$$

$$a_{i,t} = \eta + a_{i,t-1} + \varepsilon_{i,t}, \quad \varepsilon_{i,t} \sim \mathbb{N}(0, \sigma^2). \tag{12}$$

Empirical model 3

- Under these assumptions:

$$
\begin{aligned}
r^*_{i,t} &= c - \eta\delta_{i,t} - \boldsymbol{z}'_{i,t}\boldsymbol{\beta} - \sum_{j=t-\delta_{i,t}+1}^{t} v_j - u_{i,t} \\
&= c - \eta\delta_{i,t} - \boldsymbol{z}'_{i,t}\boldsymbol{\beta} - \sum_{j=1}^{T} \gamma_j d_{i,t}(j) - u_{i,t},
\end{aligned}
$$

where

$$
\delta_{i,t} \equiv \left(t - \tau_{i,t}\right),
$$

$$
d_{i,t}(j) = \begin{cases} 1, & \text{if } j \in \left[t - \delta_{i,t} + 1, t\right] \\ 0, & \text{otherwise} \end{cases}. \tag{13}
$$

and

$$
u_{i,t} \equiv \sum_{\boldsymbol{j=t-\delta_{i,t}+1}}^{\boldsymbol{t}} \varepsilon_{i,j} \sim \mathbb{N}(0, \delta_{i,t}\sigma^2).
$$

Empirical model 4

- Define the observable variable $r_{i,t}$ as

$$r_{i,t} = \begin{cases} 1, & \text{if } p_{i,t} > p_{i,t-1} \\ 0, & \text{if } p_{i,t} = p_{i,t-1} \\ -1, & \text{if } p_{i,t} < p_{i,t-1} \end{cases} . \tag{14}$$

- Define $\boldsymbol{w}_{i,t} = (\delta_{i,t}, \boldsymbol{z}'_{i,t}, \boldsymbol{d}'_{i,t})'$, where $\boldsymbol{d}_{i,t} = (d_{i,t}(1), ..., d_{i,t}(T))'$

- Then:

$$Pr[r_{i,t} = 1|\boldsymbol{w}_{i,t}] = Pr[r^*_{i,t} \leq s|\boldsymbol{w}_{i,t}]$$

Empirical model 5

$$
\begin{aligned}
Pr[r_{i,t}=1|\boldsymbol{w}_{i,t}] &= Pr[r^*_{i,t} \leq s|\boldsymbol{w}_{i,t}] \\
&= Pr[c-\eta\delta_{i,t}-\boldsymbol{z}'_{i,t}\boldsymbol{\beta}-\sum_{j=1}^{T}\gamma_j d_{i,t}(j)-u_{i,t} \leq s|\boldsymbol{w}_{i,t}] \quad (15)\\
&= Pr\left[\frac{u_{i,t}}{\sqrt{\delta_{i,t}}\sigma} \geq \frac{c-s-\eta\delta_{i,t}-\boldsymbol{z}'_{i,t}\boldsymbol{\beta}-\sum_{j=1}^{T}\gamma_j d_{i,t}(j)}{\sqrt{\delta_{i,t}}\sigma}\right] \\
&= 1-\Phi\left(\frac{c-s}{\sigma}\frac{1}{\sqrt{\delta_{i,t}}}-\frac{\eta}{\sigma}\sqrt{\delta_{i,t}}-\frac{\boldsymbol{z}'_{i,t}}{\sqrt{\delta_{i,t}}}\frac{\boldsymbol{\beta}}{\sigma}-\sum_{j=1}^{T}\frac{\gamma_j}{\sigma}\frac{d_{i,t}(j)}{\sqrt{\delta_{i,t}}}\right) \\
&= 1-\Phi\left(\pi_1\ddot{\mathbf{1}}_{i,t}-\tilde{\eta}\ddot{\delta}_{i,t}-\ddot{\boldsymbol{z}}'_{i,t}\tilde{\boldsymbol{\beta}}-\sum_{j=1}^{T}\tilde{\gamma}_j\ddot{d}_{i,t}(j)\right)
\end{aligned}
$$

variables with two dots are divided by $\sqrt{\delta_{i,t}}$,

parameters with tilde are scaled by σ, $\pi_1=(c-s)/\sigma$.

Empirical model 6: ordered probit model

- **Probability of price increase**:

$$Pr[r_{i,t} = 1|\boldsymbol{w}_{i,t}] = 1 - \Phi\left(\pi_1 \ddot{\mathbf{1}}_{i,t} - \tilde{\eta}\ddot{\delta}_{i,t} - \ddot{\boldsymbol{z}}'_{i,t}\tilde{\boldsymbol{\beta}} - \sum_{j=1}^{T} \tilde{\gamma}_j \ddot{d}_{i,t}(j)\right)$$

- **Probability of keeping the price:**

$$\begin{aligned} Pr[r_{i,t} &= 0|\boldsymbol{w}_{i,t}] = \Phi\left(\pi_1 \ddot{\mathbf{1}}_{i,t} - \tilde{\eta}\ddot{\delta}_{i,t} - \ddot{\boldsymbol{z}}'_{i,t}\tilde{\boldsymbol{\beta}} - \sum_{j=1}^{T} \tilde{\gamma}_j \ddot{d}_{j,t}\right) \\ &\qquad \ldots\ldots - \Phi\left(\pi_0 \ddot{\mathbf{1}}_{i,t} - \tilde{\eta}\ddot{\delta}_{i,t} - \ddot{\boldsymbol{z}}'_{i,t}\tilde{\boldsymbol{\beta}} - \sum_{j=1}^{T} \tilde{\gamma}_j \ddot{d}_{i,t}(j)\right) \end{aligned}$$

- **Probability of price decrease:**

$$Pr[r_{i,t} = -1|\boldsymbol{w}_{i,t}] = \Phi\left(\pi_0 \ddot{\mathbf{1}}_{i,t} - \tilde{\eta}\ddot{\delta}_{i,t} - \ddot{\boldsymbol{z}}'_{i,t}\tilde{\boldsymbol{\beta}} - \sum_{j=1}^{T} \tilde{\gamma}_j \ddot{d}_{i,t}(j)\right)$$

Empirical model 7: estimation

- Estimation by quasi-maximum likelihood controling for:
  - dependence on the cross-section due to common macro shocks
  - autocorrelation and heteroskedasticity that emerge from structural model
- Robust variance-covariance matrix with non-parametric correction à la Newey-West.
- Asymptotics:
  - $N \rightarrow \infty$
  - $\frac{T}{N} \rightarrow 0$

Empirical model 8: identification

Real rigidity parameter:

$$\zeta = \frac{\tilde{\beta}_1}{\tilde{\beta}_1 + \tilde{\beta}_2}. \tag{16}$$

$$\sigma = \frac{1}{\tilde{\beta}_1 + \tilde{\beta}_2}. \tag{17}$$

Pricing rule parameters:

$$c - S = \pi_1 \sigma$$

$$S - c = \pi_0 \sigma$$

$$S - s = (\pi_1 - \pi_0)\, \sigma$$

Data: microdata

- Price quotes from Brazilian CPI calculated by FGV, from 1996 to 2006.

- Typical item: type 1 rice of the Combrasil brand, sold in a 1kg package in a given outlet, in Rio de Janeiro.

- Each item is surveyed once a month in Rio and São Paulo.

- Characterization of price-setting using Brazilian micro data:
  - Gouvea (2007) uses this same sample;
  - Barros, Bonomo, Carvalho and Matos (2010) uses the whole FGV CPI from 1996 to 2010.

- Treatment:
  - sales V filter
  - exclude products with problematic price quotes (Eichenbaum et al 2012)
- After exclusions we were left with 178 products and services with all seven sectors still represented, accounting for 40.4% of all prices in the CPI-FGV.
- Robustness: estimation without exclusions

Results 1: Baseline estimation

$\mathcal{Y}_t$	p_t	e_t	ζ	Conf. int for ζ	
0.60	9.57	0.11	0.06	0.05	0.07
(0.077)	(0.049)	(0.049)	(0.012)		

Results 2: Robustness

Model	$\mathcal{Y}_t$	p_t	e_t	ζ	C. i. for ζ	
Period 1997 - 2000	0.15	4.93	0.62	0.03	-0.03	0.09
	(0.160)	(0.146)	(0.024)	(0.031)		
Period 2001 - 2004	1.29	11.07	-0.40	0.10	0.09	0.12
	(0.094)	(0.054)	(0.015)	(0.007)		
Without Exchange Rate	2.93	3.43	–	0.46	0.44	0.48
	(0.074)	(0.037)		(0.008)		
Idiosyncratic White Noise	0.90	12.72	0.05	0.07	0.05	0.09
	(0.112)	(0.072)	(0.018)	(0.008)		
Without promotions	0.53	8.90	0.02	0.06	0.04	0.07
	(0.079)	(0.050)	(0.013)	(0.008)		
Without exclusions	0.44	9.79	0.03	0.04	0.03	0.05
	(0.065)	(0.044)	(0.011)	(0.006)		

Results 3: pricing rule

$\pi_0 = \frac{c-S}{\sigma}$	$\pi_1 = \frac{c-s}{\sigma}$	σ	$c - s$	$S - c$	Size of in. range
-0.92 (0.01)	0.62 (0.01)	0.10 (0.01)	0.06	0.09	0.15

- σ reasonable (same value obtained by Klenow and Willis without strategic complementarity).

- negative adjusments are larger than positive adjustments, as in the sample.

- adjustments sizes are smaller than in the sample:
  - estimation does not use adjustment size, but frequency of adjustments
  - downward bias due to heterogeneity and non-linearity in the relation size - frequency.

Results 4: actual, frictionless, and reset price inflation

- We compare statistics of:
  - actual FGV CPI inflation π
  - frictionless inflation π^*- inflation that would occur if there were no nominal rigidities:
    - recovered with base on our estimation of p^* equation;
    - in our setup (Ss rules) coincides with theoretical reset price inflation.
  - empirical reset price inflation $\hat{\pi}^*$, proposed by Bils, Klenow and Mahlin (2009), which is different from the theoretical reset price inflation due to selection of price changers.

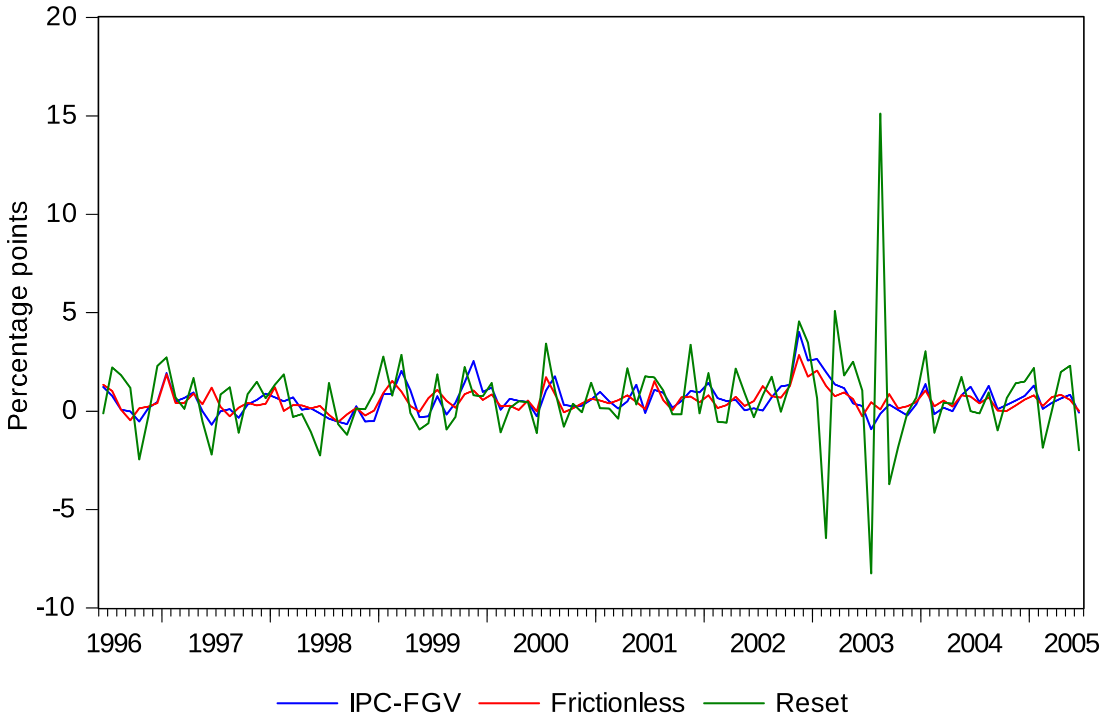
Empirical reset price

$$\hat{p}^*_{i,t} = \begin{cases} p_{i,t}, & if\ p_{i,t} \neq p_{i,t-1} \\ \hat{p}^*_{i,t-1} + \hat{\pi}^*_t, & if\ p_{i,t} = p_{i,t-1} \end{cases}, \tag{18}$$

where $\hat{\pi}^*_t$ is given by:

$$\widehat{\pi}^*_t \equiv \frac{\sum_i \omega_{i,t} \left(p_{i,t} - \hat{p}^*_{i,t-1} \right) I_{i,t}}{\sum_i \omega_{i,t} I_{i,t}}.$$

Actual, frictionless and reset price inflation



Note: Frictionless inflation corresponds to the average obtained across the 1000 simulations. Actual inflation is calculated among products left after exclusions. Reset inflation is obtained using BKM's methodology.

Figure 1: Frictionless, reset and actual price inflation

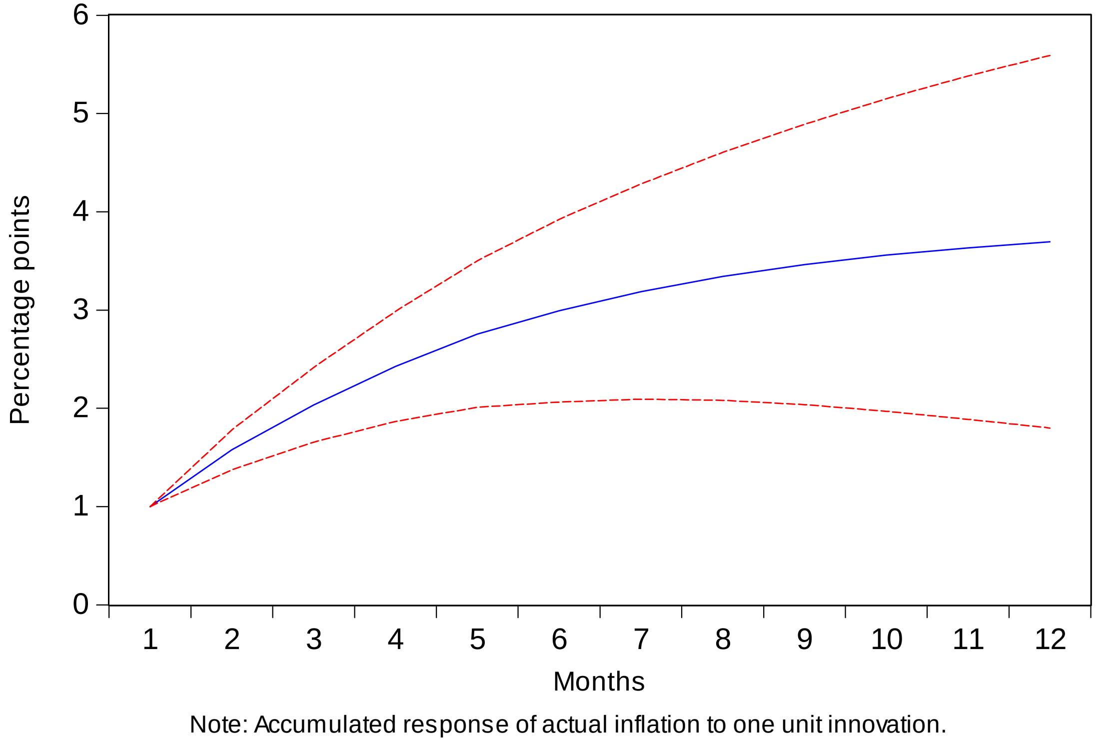
Actual, frictionless and reset price inflation

Series	Std deviation	Persistence
Actual Inflation IPC-FGV	0.76%	0.51
Frictionless Inflation	0.72%	0.21
Reset Price Inflation	2.30%	-0.35

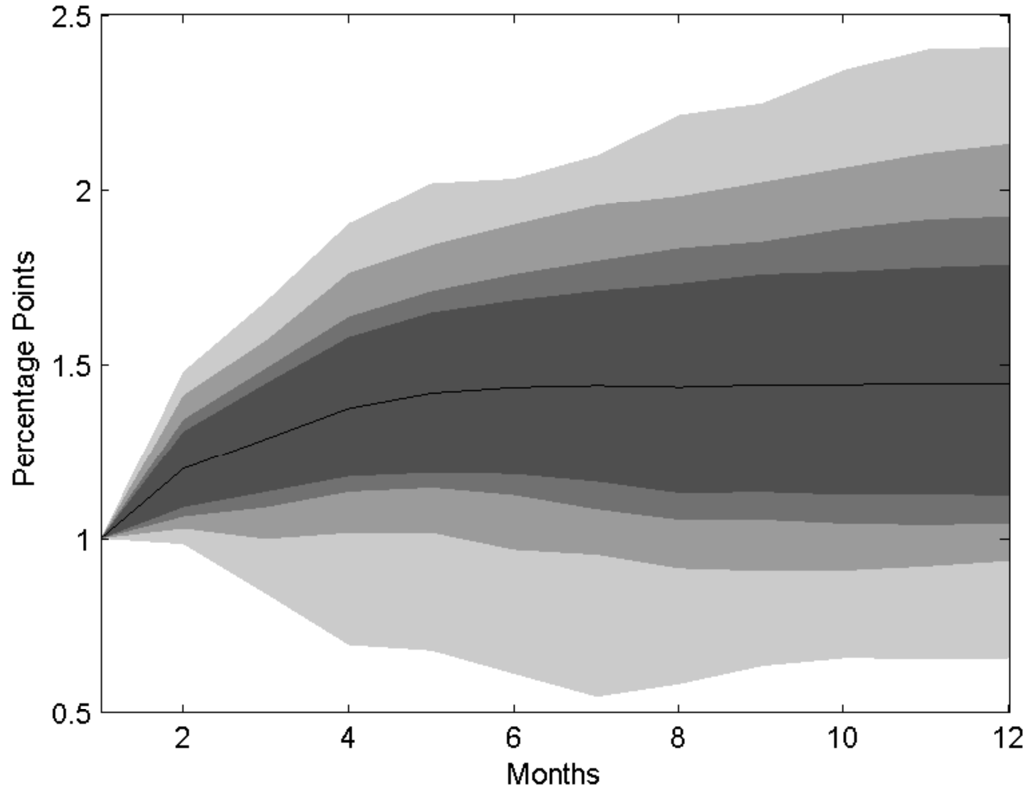
Results 5: IRFs of frictionless, and reset price inflation

- Following BKM we estimate an AR(6) for π^* and $\hat{\pi}^*$ and graph a IRF for p^* and $\widehat{p}^*$following a 1% impulse:
  - IRF for p^* is upward sloping, which is consistent with strong strategic complementarities.
  - Response for $\widehat{p}^*$ is greater on impact, resembling that obtained by BKM

Results 5: IRFs of actual, frictionless, and reset price inflation



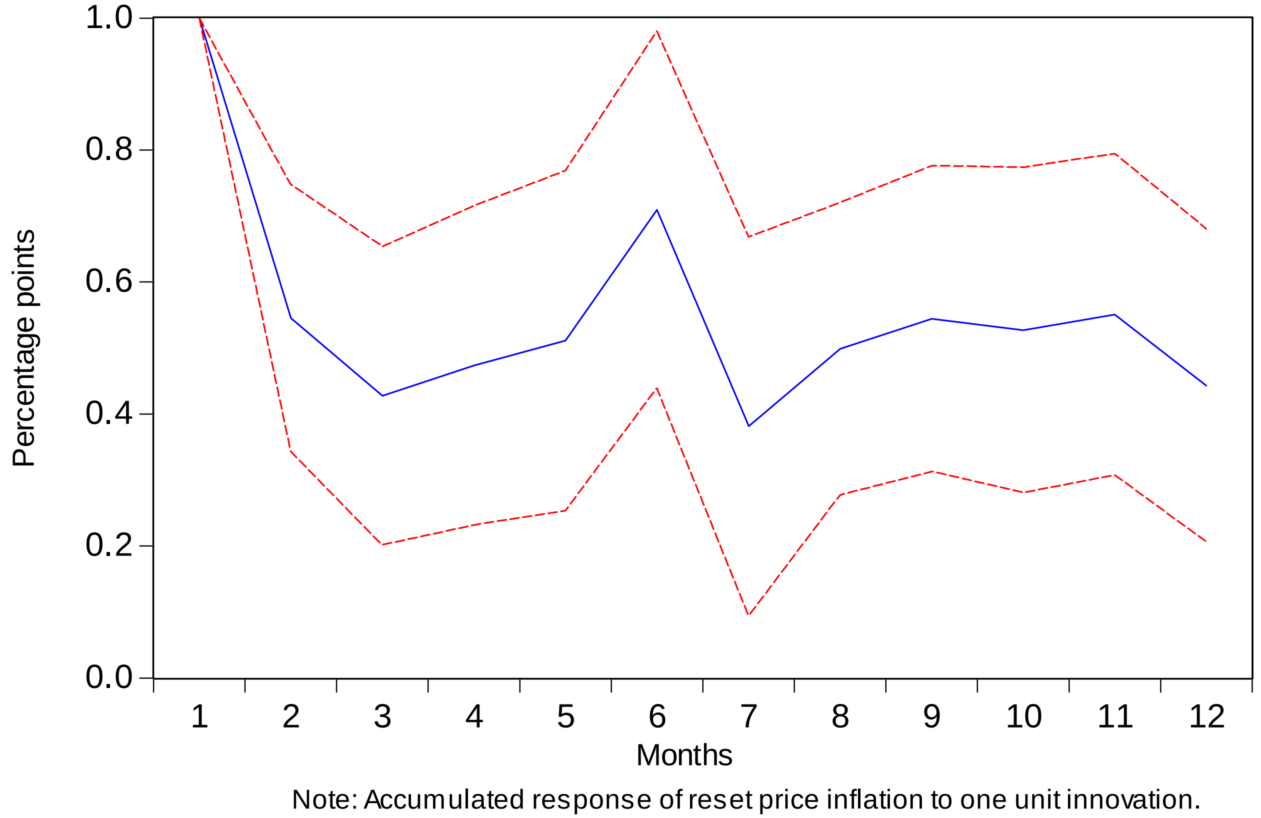
Impulse response of actual inflation



Note: Accumulated responses of frictionless optimal price inflation to one unit innovation

Impulse response of estimated frictionless optimal price, baseline specification

Results 5: IRFs of frictionless, and reset price inflation



Impulse response of estimated reset price, using BKM's methodology

Evaluating results

- Properties of $\hat{\pi}^*$ are similar in US and Brazilian data

- π^* is less variable and more persistent than $\hat{\pi}^*$:

  – $\hat{\pi}^*$ is influenced by the selection effect, but not π^* (where Ss rules took care of it)

  – π^* reflects more directly strategic complementarity

- Of course, our results depend on pricing rule being of the Ss type.

Conclusions

- Direct estimation of complementarity parameter with base on micro data:
  - need to assume some pricing rule
  - does not depend on the demand side
- Strong strategic complementarities found in micro data.
  - we did not use macro effects of shocks in the estimation;
  - could lead to significant macro effects.
- Our methodology recovers frictionless optimal price:
  - a fundamental variable.
  - it is not influenced by selection effect.