Large Shocks in Menu Cost Models*

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Abstract

Real effects of monetary policy shocks in menu cost models depend crucially on the distribution of the size of price changes. With a realistically high kurtosis, Midrigan (2011) overturned the standard Golosov and Lucas (2007) result of small and temporary real effects and found them nearly as large as in time-dependent pricing models (Calvo, 1983). In this paper we show, however, that this result hangs on assuming both small aggregate shocks and no trend inflation. For larger shock sizes (of magnitude from 1-3%) or positive trend inflation, the influence of the distribution turns around and the monetary policy effectiveness in Midrigan's model gets even smaller, or, equivalently, the inflation pass-through of aggregate shocks gets even higher than in the Golosov-Lucas model. The reason is that with leptokurtic shocks, for large aggregate shocks or trend inflation, the extensive margin starts playing a quantitatively important role; a channel that is missing from standard time-dependent pricing models, and is quantitatively weak in the Golosov-Lucas model. We also show that the interaction of leptokurtic shocks with trend inflation (Ball and Mankiw, 1994) implies a quantitatively important asymmetry between the inflation pass-through (and the real effects) of positive and negative monetary policy shocks. We present evidence for very high positive and small negative inflation pass-throughs in a natural experiment of large value-added tax shocks in Hungary, that are in line with the quantitative predictions of Midrigan's calibrated menu cost model.

1 Introduction

Standard time dependent pricing models (like Calvo, 1983) are ill suited to analyze price level reactions to large aggregate shocks, because they assume time-invariant fraction of price changes, or, in other words, no adjustments on the extensive margin. Though this assumption seems valid for normal periods

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in low-inflation environments like the US before the crisis (see Klenow-Krystov, 2008), preliminary evidence suggests that even the US witnessed a significant change in the price changing frequency during the 2007-2009 crisis (Klenow-Malin, 2010). Large shocks, as a result of large exchange rate devaluations, sales or value added tax changes, or large monetary policy shocks that influence the frequency of price changes, do appear from time to time in both developed and emerging economies (e.g. Mexico in 1994, or numerous VAT changes in European countries, see Gagnon, 2008 and the references there). Menu cost models, in which firms endogenously choose whether to respond to aggregate shocks for a small cost, provide a suitable framework to address these events.

The magnitude of the inflation pass-through of these shocks are important as they directly influence these models' predictions on the real effects of monetary policy shocks. Golosov and Lucas, 2007 argued that in a calibrated quantitative menu cost model with normally distributed idiosyncratic shocks, there will be a high inflation pass-through (and low real effects) of a monetary policy shock. The reason is the high selection effect, coming from the interaction of the interaction of the idiosyncratic and the aggregate shocks. In case of a positive monetary policy shock, there will be two groups of firms marginally influenced by the change: those who would not have changed their prices, but now they choose to increase it, and those who would have decreased their prices, but now they choose to keep them constant. The relatively high proportion of the first group in the Golosov and Lucas, 2007 model implies the strong selection effect, and high inflation pass-through. Note, that the selection effect implies extensive margin effect: there will be an increase in the frequency of price changing firms. Midrigan, 2011 showed, however, that by correctly accounting for the high kurtosis of the price change distribution, the selection effect (and the extensive margin effect) gets smaller: the proportion of new price increasing firms and the new price non-decreasing firms are very close to each other.

We show that with large shocks or trend inflation[1], the model of Midrigan, 2011 with realistic leptokurtic shocks implies *higher* inflation pass-through (thereby lower real effects) than the model of Golosov and Lucas, 2007. We show in a similarly calibrated model, that, in the baseline with 0 inflation rate, an aggregate shock increasing the marginal cost by 2.5% implies a higher inflation pass-through in the model of Midrigan, 2011 than a similar shock in the model of Golosov-Lucas, 2007. For a yearly inflation rate of 2%, a 0.6% shock is enough to turn around the results, and above a 3% inflation rate, there is no shock-size, where the pass-through is smaller in Midrigan, 2011 than in Golosov and Lucas, 2011. Furthermore, the pass-through gets very high quickly with the leptokurtic shock of Midrigan, 2011: it reaches an immediate 95% pass-through (basically no quantitatively significant real effects) with a shock size of 4.5%, while a similar immediate pass-through in the Golosov-Lucas, 2007 model requires a shock-size of almost 20%.

These results come from the leptokurtic shock assumption of Midrigan, 2011.

[1] Midrigan, 2011 considers normal times with small shocks: the monthly standard deviation of his money supply process is 0.0018 with a persistence parameter of 0.61. He assumes no inflation.

To understand this, it is useful to differentiate between two sources of price changes: the desired price change distribution and the adjustment hazard. The first depicts the distribution of optimal price changes firms would choose in case of no menu costs, while the second determines the probability of price changes for each desired price change. The actual price change distribution is obtained by the product of these two functions. The leptokurtic shock assumption influences both. First, we need relatively small menu costs to get a realistic average price change frequency. The reason is that the price changing firms are those facing relatively higher idiosyncratic shocks, and with the leptokurtic shocks a high mass of firms face small shocks, and only a few firms face large ones. So the cutoff needs to be small. It results in a narrow adjustment hazard, or, equivalently, a narrow inaction region. This implies that a lower aggregate shock size is enough to push a substantial mass of firms over their inaction threshold. The leptokurtic distribution of idiosyncratic shocks, furthermore, implies a leptokurtic distribution of desired price changes. This implies a small frequency effect of small shocks, but large and highly non-linear effects for large shocks. The reason is that for small shocks the price-increasing mass of firms in the upper tail are symmetric to the non-price decreasing firms in the lower tail. For large shocks, however, the high mass of firms facing small idiosyncratic shocks will choose to increase their prices, and they will quickly dominate the non-price decreasing firms in the lower tail. The inflation rate influence these results, because it influences the relative position of the desired price change distribution (higher inflation means higher desired price increases) to the adjustment hazard (that is quantitatively unaffected by the inflation rate).

With leptokurtic shocks, even low trend-inflation introduces a quantitatively significant *asymmetry* in the inflation pass-throughs: positive shocks will have much higher pass-through (and smaller real effects) than negative shocks. As argued by Ball and Mankiw, 1994, trend inflation introduces asymmetric inflation reaction to aggregate shocks in menu cost models. As they showed, this aggregate asymmetry would not be true either under flexible price assumption or time-dependent pricing models, like Calvo (1983). The main reason is that the effect comes from endogenous asymmetric selection effect missing in standard models: facing a positive shock in an inflationary environment, the relative proportion of price-increasing firms to the price-decreasing ones is higher than the relative proportion of price-decreasing firms to price increasing ones in case of a negative shock.

Though this asymmetric selection effect is present in the model of Golosov and Lucas, 2007, we show that it is quantitatively small. In models with leptokurtic shocks, however, we show that the asymmetric selection effect is quantitatively much higher. The reason is the different development of the slope of the desired price change distribution in these models. This slope is small for larger desired price changes, but gets very high close to the median desired price changes. As inflation shifts the desired price distribution relative to the adjustment hazard, these different slopes would imply very different selection effects for positive and negative shocks. Inflation would push the high slope region of the distribution closer to the positive inaction threshold and push the low slope region of the distribution closer to the negative inaction threshold. An additional positive shock, thereby, would make much more firms increase their prices relative to the firms that choose not to decrease it, compared to the effects of a negative shock, where there would be less firms choosing to decrease their prices relative to the firms that choose not to increase them.

We show that a model with leptokurtic shocks similar to Midrigan, 2011 calibrated to hit standard moments of price change distribution during normal times can successfully reproduce pass-through and frequency responses to large value-added shocks. In Hungary, the fiscal authorities sequentially closed the gap between two VAT tax rates levied on two sets of products. In January 2006, they have decreased the higher rate from 25% to 20% and in September 2006, they have increased the lower rate again from 15% to 20%. These large VAT changes are measurable and transparent cost push shocks directly influencing the gross prices of affected firms, which are the quoted prices in Hungary – differently from the U.S. practice regarding sales tax, but similarly to most other European countries. [2] The fact that this cost push shock dominated the inflation effects during these months is also supported by the fact the monetary authority has expressed in advance that it was prepared to fully accommodate the direct inflation effects of both the positive and the negative VAT changes.

We use store level data collected for the compilation of the consumer price index. We concentrate on the processed food sector, which is the largest in our sample and, where the moments of groups facing the lower and the higher tax rates are close to each other. The moments in this sector are also close to the moments in the sample of Midrigan, 2011, who is using US supermarket scanner data. The 5% points positive shock caused a very high immediate pass-through response of 98.8% and a relatively low immediate response of 32.9% to the 5% points negative shock. The frequency responses were similarly skewed with a 60% for the positive shock and a 29.4% to the negative shock, while the normal frequency was 13.5% in our sample. The Golosov and Lucas model calibrated to hit the moments during normal times significantly underestimates these frequency increases during the tax shocks: the responses are between 17%-23%. The pass-through responses, similarly, are between 44%-49%, that seriously underestimates the positive shocks, and overestimates the negative ones. The model of Midrigan, 2011, however, predicts pass-throughs of 1.15% for the positive shocks and a 47.8% pass-through for the 5% negative shock. They somewhat overestimate the pass-throughs, but are much closer to the observed results than the Golosov-Lucas, 2007 model. They predict a frequency of 72.8% for the positive shocks and 34.7% for the negative shock that are also spectacular predictions given we had no free parameters to match these moments. Furthermore, the leptokurtic model is able to qualitatively match the fact that the average absolute size of price changes actually *decreased* during both the positive and the negative shocks.

The paper is structured as follows. In section 2, we present the our model

[2]This practice is also reinforced by a consumer protection law requiring also that "consumers can not be forced to calculate prices in their head". 1997.CLV. Law on Consumer Protection and 7/2001. (III. 29.) Ministry of Economy decree and its explanation.

version of Midrigan, 2011, the model's calibration. In section 3, we show how the predictions of our model compares to the Golosov-Lucas, 2007 model for different shock sizes and inflation rates. In section 4, we present the Hungarian VAT experiment and our data and show the predictive ability of our model and the Golosov and Lucas, 2007 model. Section 5 concludes.

2 The Model

To investigate the effects of large tax shocks in menu cost models, we use a standard Golosov and Lucas (2007)-style heterogenous firm menu cost model with value-added taxes, and leptokurtic idiosyncratic productivity shocks, as in Midrigan (2011). We also assume a simple form of heterogeneity in menu costs by allowing a constant fraction a firms each period having zero menu cost; Midrigan (2011) argues that this model has the same qualitative predictions for the real effect of nominal shocks as a more realistic one with multi-product firms.[3]

2.1 Consumers

The representative consumer consumes a Dixit-Stiglitz aggregate (C) of a basket of individual goods i, holds real balances M/P and supplies labor L to maximize the expected present value of her utility in each period t:

$$\max_{\{C_t(i), L_t, M_t\}} E \sum_{t=0}^{\infty} \beta^t \left(\log \left[C_t \cdot \left(\frac{M_t}{P_t} \right)^{\nu} \right] - \frac{\mu}{1+\psi} \left(L_t \right)^{1+\psi} \right), \tag{1}$$

where μ is the disutility of labor, ψ is the inverse Frisch-elasticity of labor supply, and aggregate consumption C_t is a constant elasticity of substitution aggregate of individual good consumptions $C_t(i)$:

$$C_t = \left(\int_{\mathcal{N}} (N)^{-\frac{1}{\theta}} C_t(i)^{\frac{\theta-1}{\theta}} di \right)^{\frac{\theta}{\theta-1}}.$$

Here θ is the constant elasticity of substitution between different products, $\mathcal{N}$ is the set of the products, and N is their measure, which we normalize to 1.

The consumer's budget constraints for all time period t and history h^t are given[4] by

$$\int_{\mathcal{N}} P_t(i) C_t(i) di + \int_{h_{t+1}} B_{t+1}(h_{t+1}) dh_{t+1} + M_{t+1} = R_t B_t + M_t + \tilde{w}_t L_t + \tilde{\Pi}_t + T_t, \tag{2}$$

[3] Multi-product firms and heterogenous menu cost models – unlike simple menu cost models – both generate some small price changes, therefore better match the empirical distribution of the size of price changes.

[4] Dependence on history is suppressed for notational convenience.

where $P_t(i)$ is the gross price (including taxes), $B_t(h_t)$ is a nominal Arrow-security with state dependent gross return R_t, M_t is the nominal money balance, $\tilde{w}_t$ is nominal wage, $\tilde{\Pi}_t$ is nominal profits, and T_t is a lump-sum transfer.

In order to express the consumer's optimality conditions in a convenient form, it is useful to define the aggregate (P_t) price level by

$$P_t = \left(\int_{\mathcal{N}} \frac{P_t(i)^{1-\theta}}{N} di \right)^{\frac{1}{1-\theta}},$$

which is a standard definition, implying that the aggregate expenditure is given by $P_t C_t$.

Then the representative consumer's demand for each individual good i can be expressed as

$$C_t(i) = \frac{C_t}{N} \left(\frac{P_t(i)}{P_t} \right)^{-\theta}. \tag{3}$$

The Euler equation of the consumer implies that the stochastic discount factor $\frac{1}{R_{t+1}}$ is

$$\frac{1}{R_{t+1}} = \beta \frac{P_t C_t}{P_{t+1} C_{t+1}}, \tag{4}$$

and the labor supply and money demand equations are given by

$$\mu L_t^{\psi} C_t = \frac{\tilde{w}_t}{P_t}, \tag{5}$$

$$\frac{M_t}{P_t} = \nu C_t \frac{i_t + 1}{i_t}, \tag{6}$$

where i_t is the nominal interest rate.

2.2 The government and the central bank

We assume that firms face an exogenously given value-added tax rate of τ_t, that they do not expect future changes in this, but can respond to any changes in this tax rate immediately. The government's tax revenues are assumed to be redistributed in a lump sum fashion:[5]

$$\frac{\tau_t}{1+\tau_t} P_t C_t = T_t^g.$$

As general in this literature, the central bank is assumed to follow a nominal income targeting rule by maintaining a predetermined growth rate (g_{PY}) of the nominal aggregate output ($P_t Y_t$), which we assume to be equal to the money supply (M_t). The exogenous nominal growth assumption substantially simplifies the analysis, allowing us to focus on firm level incentives for responding to tax

[5] If the net prices P^n are taxed by a value-added tax of τ, then the gross price is $P = (1+\tau)P^n$, so the tax revenue equals $\tau P^n C = \frac{\tau}{1+\tau} PC$.

changes.[6] The resulting extra money supply M_t in the economy is redistributed in a lump sum way

$$M_t - M_{t-1} = T_t^m,$$

where $T_t^m + T_t^g = T_t$ is the total transfer to the consumers.

2.3 The firms

We introduce value-added taxes (VAT) to the model in a straightforward way: as we do not model explicitly the production process, for us VAT is equivalent to a standard sales tax. We assume that firms set gross prices (including VAT)[7] and they need to pay a fixed menu cost in case they decide to change these gross prices.

Each firm i is assumed to produce product i monopolistically, post gross prices $P_t(i)$ and satisfy all demand given this price. However, if they choose to change their gross nominal prices relative to the previous period, they must use a small amount, $\tilde{\phi}_t(i)$ hours of extra labor input. Following Midrigan (2011), we allow $\tilde{\phi}_t(i)$ to take on two different values: in each time period for each firm, it will be 0 with probability κ and $\tilde{\phi}$ with probability $1-\kappa$.[8] As Midrigan shows, allowing this simple heterogeneity in menu costs leads to a model that has similar predictions for the real effect of nominal shocks as his model with multi-product firms; so we study this particular model with heterogenous menu costs as an approximation of Midrigan's multi-product model.

The firms' problem is to maximize the expected discounted present value of their profits

$$\max E \sum_{t=0}^{\infty} \frac{1}{\prod_{q=0}^{t} R(q)} \tilde{\Pi}_t(i), \tag{7}$$

where the periodic profit level – without menu costs – is

$$\tilde{\Pi}_t(i) = \frac{1}{1+\tau_t(i)} P_t(i) Y_t(i) - \tilde{w}_t L_t(i). \tag{8}$$

We assume that firms use a constant returns to scale technology with a single production factor of labor to produce their differentiated good i, and face idiosyncratic and aggregate technology shocks $A_t(i)$ and Z_t. The production functions of the firms are given by

$$Y_t(i) = Z_t A_t(i) L_t(i). \tag{9}$$

We assume that the aggregate technology shock Z_t grows at a constant rate g_Z. The difference between the growth rate of nominal expenditures (g_{PY}) and aggregate technology (g_Z) will determine the trend inflation (π). By assuming

[6] The constant nominal GDP growth assumption would be restrictive if we wanted to consider endogenous monetary policy responses to the tax shocks.

[7] We study episodes of large VAT-changes in Hungary in Section 4, and it is a legal requirement in Hungary that firms should post the gross prices.

[8] Menu cost draws are i.i.d. across firms and over time.

deterministic growth rates, we rule out inflation variability. This assumption, together with the one of no other sources of aggregate uncertainty, simplifies the numerical algorithm we use and has no significant effects on the results.[9]

Idiosyncratic productivity shocks $A_t(i)$ are the now standard assumption of Golosov and Lucas (2007) to reproduce the observed large size of average price changes. The log of the idiosyncratic productivity is assumed to follow an AR(1) process:

$$lnA_t(i) = \rho_A lnA_{t-1}(i) + \varepsilon_t(i), \tag{10}$$

where the innovations are i.i.d. random variables with mean zero and variance σ_A^2. We follow Gertler and Leahy (2008) and Midrigan (2011) in assuming leptokurtic (Poisson) distribution for the idiosyncratic technology shock innovations, which is necessary to reproduce the excess kurtosis of the distribution of the size of price changes. Specifically, to generate this extra kurtosis we assume that $\varepsilon_t(i)$ is zero with probability p, but with probability $1-p$ it is drawn from a normal distribution with mean zero and variance $\frac{\sigma_A^2}{1-p}$.[10] A higher parameter p will increase the kurtosis of the idiosyncratic productivity shock innovations. Note that by setting $p = 0$, we have the model with normally distributed idiosyncratic productivity innovations, as in Golosov and Lucas (2007).

The production function (9) implies an individual an aggregate labor demand

$$L_t(i) = \frac{Y_t(i)}{Z_t A_t(i)}, \tag{11}$$

$$L_t = \int_{\mathcal{N}} L_t(i)di. \tag{12}$$

Substituting the individual demand (equation (3)) and the labor demand (equation (11)) into the periodic profit function (8) and using the equilibrium condition $Y_t(i) = C_t(i)$, the profit function becomes

$$\tilde{\Pi}_t(i) = \frac{1}{1+\tau_t}\frac{1}{N}P_t(i)\left(\frac{P_t(i)}{P_t}\right)^{-\theta} Y_t - \tilde{w}_t \frac{\frac{1}{N}\left(\frac{P_t(i)}{P_t}\right)^{-\theta} Y_t}{Z_t A_t(i)}.$$

As we have constant nominal growth in the model, we can normalize nominal profits with the average revenues

$$\Pi_t(i) = \frac{\tilde{\Pi}_t(i)N}{P_t Y_t}.$$

Let $p_t(i) = \frac{P_t(i)}{P_t}$ be the relative price, $w_t = \frac{\tilde{w}_t}{P_t Y_t}$ the normalized wage rate, and $\zeta_t = w_t \frac{Y_t}{Z_t}$ be an aggregate cost factor. Substituting these variables into the

[9] We have also solved the model under stochastic aggregate technology growth rates, but this did not change our results significantly.

[10] This ensures that the variance of $\varepsilon_t(i)$ is indeed σ_A^2.

normalized periodic profit function we obtain that

$$\Pi_t(p_t(i), A_t(i), \zeta_t) = \frac{1}{1+\tau_t}\left(p_t(i)\right)^{1-\theta} - \left(p_t(i)\right)^{-\theta}\zeta_t A_t(i)^{-1}. \tag{13}$$

Similarly, we normalize the nominal menu cost of $\tilde{w}_t\tilde{\phi}_t(i)$ by $\frac{N}{P_tY_t}$ to obtain $\phi_t(i) = Nw_t\tilde{\phi}_t(i)$ as the normalized menu cost. As we assumed that $\tilde{\phi}_t(i)$ can take only two values, 0 and $\tilde{\phi}$, the normalized menu cost will be either 0 (with probability κ) or $\phi = Nw\tilde{\phi}$ (with probability $1-\kappa$).[11]

Given the normalized profit function, the value of the firm if it chooses not to change its price is

$$V^{NC}\left(p(i), A(i)\right) = \Pi\left(\frac{p(i)}{1+\pi}, A(i), \zeta\right) + \beta EV\left(\frac{p(i)}{1+\pi}, A'(i), \phi'(i)\right), \tag{14}$$

where A' and ϕ' are the next period's idiosyncratic productivity and menu cost draws, and we used the fact that if the firm decides to keep its nominal price constant, its beginning-of-period relative price $p(i)$ is going to depreciate by the inflation rate π.[12]

If the firm chooses to change its price, it chooses the new relative price $p'(i)$ optimally, and it will also have to pay its current menu cost $\phi(i)$, so its value will be

$$V^{C}\left(A(i), \phi(i)\right) = \max_{p'(i)}\left\{\Pi(p'(i), A(i), \zeta) - \phi(i) + \beta EV\left(p'(i), A'(i), \phi'(i)\right)\right\}. \tag{15}$$

Finally, the value of the firm will be determined by its decision, i.e. whichever is higher from V^{NC} and V^{C}:

$$V\left(p(i), A(i), \phi(i)\right) = \max_{\{C,NC\}}\left[V^{NC}\left(p(i), A(i)\right), V^{C}\left(A(i), \phi(i)\right)\right]. \tag{16}$$

In this normalized firm problem, the aggregate state variables (ζ_t, π_t) are substituted with their equilibrium values (ζ, π).[13] The idiosyncratic state variables are given by $(p_t(i), A_t(i), \phi_t(i))$, with $\phi_t(i)$ having only two possible values: 0 and ϕ. This allows us to solve the problem as if we had only two state variables, $p(i)$ and $A(i)$.[14]

[11] As there is no aggregate uncertainty, the normalized wage w_t will be time-invariant, so the positive realization of the normalized menu cost (ϕ) will also be time-invariant.

[12] The expectation is taken over the future idiosyncratic productivity and menu cost draws, conditional on the current idiosyncratic productivity.

[13] If there is some aggregate uncertainty, the distribution of firms over their idiosyncratic state variables, Γ_t would also be an aggregate state variable, as it would influence the firms' expectations about the next period values of the other aggregate state variables. But without aggregate uncertainty we have an equilibrium distribution of firms, Γ, which does not influence the evolution of the idiosyncratic state variables.

[14] When $\phi_t(i) = 0$, the firm has a trivial choice: $V^C\left(A(i), 0\right) \geq V^{NC}\left(p(i), A(i)\right)$, so in this

2.4 The equilibrium

We consider a stochastic dynamic general equilibrium of the model. As there is no aggregate uncertainty in the model, firms know the steady-state values of the aggregate variables ζ, π, Γ. The equilibrium conditions are the following:

1. The representative consumer chooses $C_t(i), L_t, M_t$ to maximize her utility function (1) given her budget constraint (2), taking goods prices $\{P_t(i)\}$, the interest rates R_t and the nominal wage $\tilde{w}_t$ as given.

2. The firms are assumed to set prices $P_t(i)$ to maximize their value function (16), (14), (15), given their current relative prices $p(i)$ and exogenous state variables ($A(i)$ and $\phi(i)$), and the values of the aggregate variables (ζ, π, Γ). The firms also have correct beliefs about the random processes of the idiosyncratic productivity shock $A(i)$ and menu cost $\phi(i)$.

3. The central bank sets i_t, M_t to keep the nominal output growth g_{PY} constant, and the fiscal transfers are set in a way to imply balanced budget.

4. Market clearing in all goods markets $C_t(i) = Y_t(i)$.

5. Assets in zero net supply in nominal Arrow securities: $B_t = 0$.

6. Equilibrium in the labor market implying that the nominal wage $\tilde{w}_t$ equates aggregate labor demand (12) and labor supply (5).

2.5 Numerical solution

Under positive menu costs, the model has no closed form solution, so we use numerical methods to solve for the equilibrium. Most importantly, firms have to solve for the equilibrium values of aggregate variables (ζ, π, Γ) (the aggregate cost factor, the inflation rate and the distribution of firms over their idiosyncratic state variables). The calculation of the equilibrium inflation rate π is straightforward: given our assumptions of constant nominal money growth rate (g_{PY}) and constant aggregate productivity growth (g_Z), the equilibrium inflation rate is $\pi = g_{PY} - g_Z$.

To find the equilibrium values of the remaining two aggregate variables ζ and Γ, we use a standard iterative procedure. We start with a guess (initially the flex-price value) for the equilibrium value of the aggregate cost factor ζ_0. Given this guess ζ_0 and the equilibrium inflation rate π, we solve the firms' problem in (16), (14), (15) to obtain the individual firms' value and policy function.[15] Then we numerically calculate the steady-state distribution of firms, again using iterations. Specifically, we start from an initial distribution, and apply the

case it will be always optimal to change: $V(p(i), A(i), 0) = V^C(A(i), 0)$. When the menu cost draw is $\phi_t(i) = \phi$, then the firm will compare $V^C(A(i), \phi) = V^C(A(i), 0) - \phi$ (by equation 15) with $V^{NC}(p(i), A(i))$. So it is enough to calculate $V^C(A(i), 0)$ and $V^{NC}(p(i), A(i))$ to fully solve the firms' problem.

[15] For this,we use a fine grid of (500x101) points for the log relative prices ($\ln p$) and log idiosyncratic productivity shocks ($\ln A$).

policy function (to account for the firms' repricing decisions in each period) and the idiosyncratic shock transition probabilities (to account for the new set of idiosyncratic shocks arriving each period) to find the resulting distribution, and we do this until the distribution converges. Finally, with the equilibrium distribution of firms (Γ_0) over the $(\ln p, \ln A)$ space, we calculate the resulting average log relative price. If this is positive (negative), then our original guess for the aggregate cost factor (ζ_0) was too large (too small), so we correct it accordingly and start the whole procedure with a new ζ_1. We do this iterative procedure until the average log relative price in the resulting equilibrium distribution of firms (Γ_1) is zero.

In the paper we also study the equilibrium response to unforeseen permanent tax changes. To do so, we first obtain solutions for the equilibrium values of the aggregate variables before and after the tax changes, and also for the value and policy functions. Then we obtain an equilibrium transitional inflation path between these steady states with a shooting algorithm (details are in the appendix).

2.6 Model variants

In the paper we compare our baseline model above with the model of Golosov and Lucas (2007) and Calvo (1983). The Golosov-Lucas model is in fact nested in the baseline model, when $p = 0$ (the parameter governing the leptokurtic shape of idiosyncratic productivity shocks) and $\kappa = 0$ (the probability of obtaining zero menu cost instead of ϕ in every period). For the Calvo-model, we set $\phi = 0$ (which means that the menu cost of price change is always 0); introduce an extra parameter λ, which is the exogenous probability of price change; and modify equation 16 in the baseline model to

$$V\left(p(i), A(i)\right) = (1-\lambda)V^{NC}\left(p(i), A(i)\right) + \lambda V^{C}\left(A(i)\right),$$

which reflects that now changing or not changing the price is not the firms' decision, but it is an exogenous opportunity with probability λ.

2.7 Model calibration

For model calibration, we use basic moments from Hungarian store-level price data. Our choice is motivated by a natural experiment of large VAT-shocks in Hungary, discussed in Section 4. We stress, however, that the basic moments we use for calibration (frequency and average size of price changes, shape of the price change size distribution) are very close to the US moments in Midrigan (2011) and Golosov and Lucas (2007), so this choice of using Hungarian data has no influence on our qualitative results.

We fix some parameters exogenously. In our monthly model we set $\beta = 0.96^{1/12}$ (implying 4% yearly real rate), and the value of θ (which determines the level of competition between goods) to 5, which is a usual number used in the industrial organization literature.[16] Further, we set the persistence of the idiosyncratic technology shock ρ_A equal to 0.5, which is in between the values calibrated by Golosov and Lucas (2007) and Klenow and Willis (2006) (0.45 and 0.678). Finally, the inverse of the Frisch-elasticity (ψ) of the labor supply is set to zero, implying a perfectly elastic labor supply.

Regarding the constant growth rates of aggregate variables, we will study the model under several trend inflation rates between π =0 and π =4.2% per year (or 0 and 0.35% per month, the higher end is the trend inflation in the Hungarian processed food sector in our sample; US trend inflation in Golosov and Lucas, 2007 is 0.21% per month). We set the constant aggregate nominal growth rate to $g_{PY} = 9.34\%$ per year (or 0.78% per month), again equated to the growth rate of Hungarian nominal consumption in our sample. Then the aggregate technology growth is set at $g_Z = g_{PY} - \pi$ (that is, it is set to different values for different trend inflation rates).[17]

The remaining parameters of the model are calibrated to match basic micro facts from store-level price data in Hungary.

1. In the baseline model (model "M"), we calibrate the normalized menu cost parameter ϕ, the standard deviation of the idiosyncratic productivity shock innovations σ_A, the kurtosis of idiosyncratic productivity shocks p and the fraction of firms drawing zero menu cost (κ) to match the frequency and average (absolute) size of log price changes (0.1346 and 0.0991), the kurtosis of the observed price change size distribution (3.9768) and the interquartile range of the distribution of absolute price change sizes (0.0813).[18] Increasing the menu cost parameter decreases the frequency and increases the average size of price changes, while larger σ_A increases both the frequency and average size of price changes. A larger kurtosis parameter increases the kurtosis of the distribution of observed price change sizes. If we increase parameter κ, it will increase the interquartile range in the model by generating more small price changes.

2. In the baseline model with normally distributed shocks (model "GL") we calibrate the normalized menu cost parameter ϕ and the standard deviation of the idiosyncratic productivity shock innovations σ_A to match the frequency and average size of price changes (0.1346 and 0.0991), and set $p = 0$ and $\kappa = 0$ (the parameter governing the kurtosis of productivity shock innovations and the fraction of firms receiving zero menu cost). Obviously, in this case with normally distributed idiosyncratic productivity shocks we are unable to match the kurtosis and the interquartile range of the price change size distributions.

[16] There is no agreement about the value of θ in the menu cost literature, the values range from 3 (Midrigan, 2011) to 11 (Gertler-Leahy, 2008). Although the choice of θ influences our estimates of menu costs and the standard deviation of idiosyncratic shocks, it practically does not influence our estimates on inflation effects of tax changes.

[17] Our results would remain exactly the same if we always set $g_Z = 0$ and $g_{PY} = \pi$.

[18] In Midrigan (2011)'s US data, the frequency is 0.22, the average absolute size is 0.11, the kurtosis is 4.02, and the interquartile range is 0.08.

3. In the Calvo-model (model "C"), we set the price change frequency parameter λ equal to the frequency of price changes (0.1346), and calibrate the standard deviation of the idiosyncratic productivity shock innovations σ_A to match the average absolute size of price changes (0.0991). Again, we cannot match in this simple model the kurtosis and the interquartile range of the price change size distributions.

To sum up, we have 2-4 calibrated parameters to hit 2-4 major moments of the data. Table 1 contains the calibrated parameters in each model variants. In Midrigan's model with leptokurtic shocks, the calibrated menu cost is smaller and the calibrated variance of the productivity shock is larger because of the peak in the shock distribution: many shock realizations are concentrated around 0, meaning narrower inaction regions, and hence smaller menu costs. But on the same time, the distribution also has fatter tails, which means that a shock with smaller variance will be enough to generate the same amount of dispersion in the size of price changes. Further, the Calvo-model requires an order of magnitude higher standard deviation for the idiosyncratic productivity shocks to be able to match the large average absolute size of price changes.

Table 1: Calibration

Parameters	**Data**	**Model M**	**Model GL**	**Model C**
ϕ	–	0.010	0.018	0
σ_A	–	0.040	0.055	0.367
p	–	0.916	0	0
κ	–	0.010	0	0
λ	–	–	–	0.135

3 Inflation effects of large tax shocks

In this section, we show how the three separately calibrated model variants react to large value-added tax shocks. First we assume no trend inflation, and compare and explain the different pass-through effects of a shock. Then we introduce positive trend inflation and examine its quantitative effects on the asymmetry.

3.1 Pass-through

Figure 1 shows the simulated effects of the models: the time-dependent model (Calvo), the Golosov-Lucas, 2007 model (normal) and our model variant of Midrigan, 2011 (leptokurtic). The first figure shows the immediate pass-through of the models for different shock sizes. The pass-through (γ_t), in our case, is

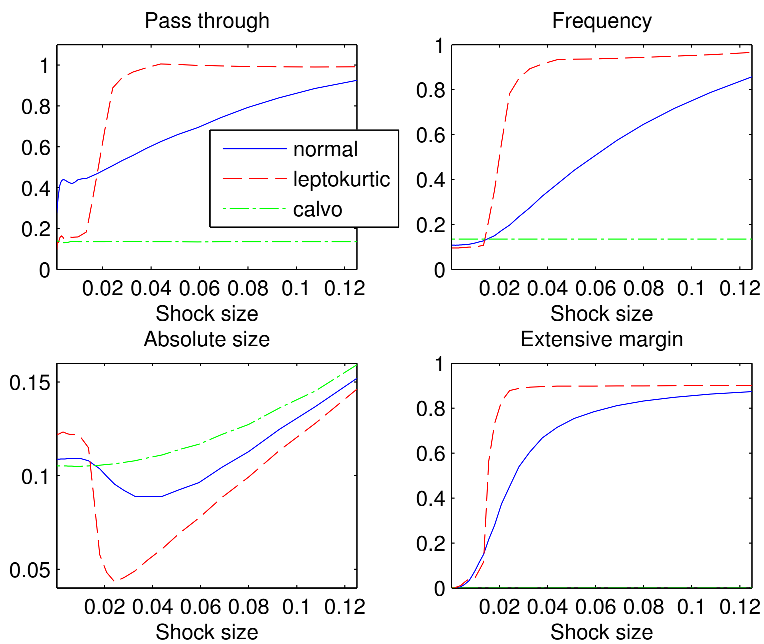

Figure 1: Effects of an aggregate VAT shock, (no inflation)

defined as the marginal effect of the tax change on the inflation rate

$$\gamma_t = \frac{\pi_t - \bar{\pi}}{\log(1+\tau_t) - \log(1+\bar{\tau})},$$

where π is the inflation rate, τ is the tax rate, and the bar stands for the steady state values. The figure shows that for the time-dependent model, the pass-through is constant at the price change probability λ. For the Golosov-Lucas, 2007 calibration, the pass-through starts around 30% and after a quick increase to 40% steadily increases with larger shock sizes. It reaches 95% immediate pass-through at close to 20% aggregate tax (marginal cost) shock. The model of Midrigan, 2011, on the other hand, implies a very low pass-through for shock sizes to around 1.5%, close to that of the time-dependent model. This is the main result of Midrigan, 2011, who argued that correctly accounting for the high kurtosis of the price change distribution would imply low pass-through and high real effects of monetary policy shocks. The figure shows, however, that for shocks higher than 1.5%, the pass-through implied by the model starts increasing quickly, surpasses the pass-through of the Golosov-Lucas, 2007 model at a shock of 2.5% and reaches a 95% immediate pass-through for a 4.5% shock. This highly non-linear development are very different from the behavior of the Golosov-Lucas, 2007 model, but, as we will show in the next section, are closer to what we saw in practice.

The second figure shows the frequency of price changing firms at the period of the shock. For smaller shocks, the frequencies are close to each other, the different pass-throughs in these region can be explained by the selection effect: in the Golosov-Lucas, 2007 model the bit higher frequency hides some important selection effects: the average price change of the newly increasing firms are higher than the average price change of the non-decreasing firms. The large increase in the pass-through in the model of Midrigan, 2011, however, is the result of large frequency increase: the price-increasing firms quickly overwhelm the price decreasing ones. As the third figure showing the average absolute size of price changes indicate, for this large-shock region, the newly changers' average price increase is smaller than the average price change. It is true for both the Golosov and Lucas, 2007 model, but much more pronounced in the model of Midrigan, 2011. The reason is that the conditional distribution of price-increasing firms gets much more skewed to the left.

The last figure shows the decomposed extensive margin effect (X_t) of the shocks, that is defined as the proportion of inflation effect caused by the increase in the frequency

$$X_t = \frac{\left(I_t - \bar{I}\right) \bar{\Delta P}}{\pi_t - \bar{\pi}}.$$

The figure shows that the extensive margin effect is present and gets very strong in both menu cost models with larger shocks, it gets high much quicker in the model of Midrigan, 2011 than in the Golosov-Lucas, 2007 model. The extensive margin effect is completely missing from the time-dependent pricing model.

3.2 Asymmetry

Ball and Mankiw (1994) argued that trend inflation in a menu cost model can explain aggregate inflation asymmetry. The theoretical argument is subtle and would not work without the menu cost assumption. It is straightforward to see why the flexible price assumption would not interact with trend-inflation: firms would adjust their nominal prices every instance to follow the aggregate inflation rate and their additional response to aggregate shocks would imply a full and symmetric pass-through. But in standard time-dependent pricing models, like Calvo (1983) and menu cost models, trend inflation introduces a firm level asymmetry in shock responses. This part of argument is relatively straightforward and rests on the facts that forward looking firms set their prices for several periods in advance and trend inflation constantly reduces their relative prices. The firms' dynamically optimal price change, thereby, is going to be higher than it would be in a static case in order to keep their constantly decreasing relative price close to its static optimum throughout their price spell. This trend-inflation induced bias would mean higher responses for positive shocks and lower responses for negative ones for every single firm.

The subtlety of the argument comes from the fact that this incentive would not translate into asymmetric response to aggregate shocks in sticky price models, where the choice to change prices is time-dependent or exogenously given (Calvo, 1983). The firms that happen to change their prices will, indeed, incorporate the effects of the trend inflation, but their *additional* (i.e. shock-induced

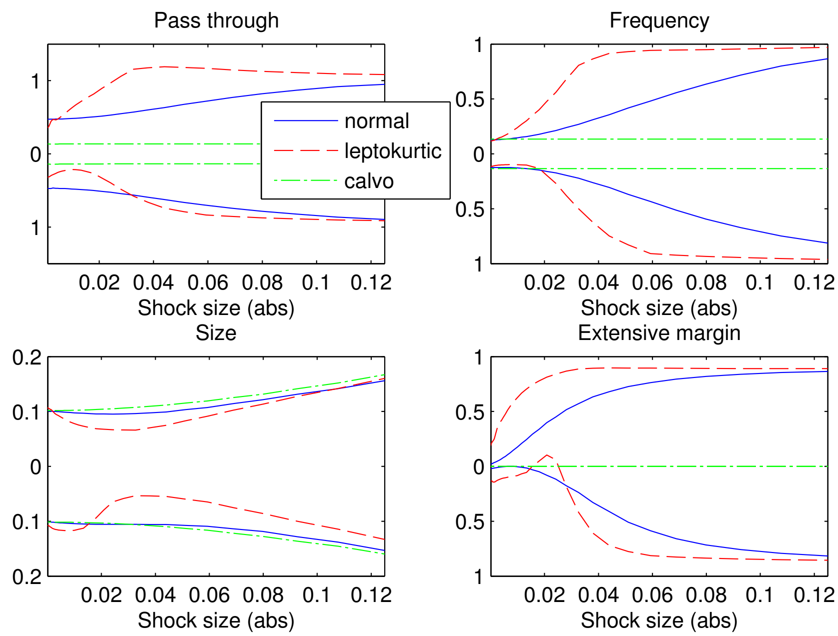

Figure 2: Effects of an positive and a negative VAT shock (2% inflation)

as opposed to trend inflation-induced) response will not be asymmetric. In other words, as a result of the firm level asymmetry, the expected price change is still going to be positive, but that just explains the trend-inflation itself and will not add to the inflation asymmetry. The main reason that results in aggregate inflation asymmetry in the menu cost models is *endogenous selection* coming from the firm level asymmetry: facing a positive shock in an inflationary environment, the relative proportion of price-increasing firms to the price-decreasing ones is higher than the relative proportion of price-decreasing firms to price increasing ones in case of a negative shock.

Figure 2 shows the quantitative effects of a positive and the mirror image of a negative VAT shocks in a model with 2% trend inflation. It shows that the pass-through advantage of the Midrigan, 2011 model disappears for a positive shock of 0.6% in this case, and the 95% pass-through is already reached at a 3.4% shock. It is important to note, however, that there is a significant asymmetry for positive and negative shocks with trend inflation for the model of Midrigan, 2011, while there is asymmetry in the time-dependent model and a quantitatively small asymmetry in Golosov-Lucas, 2007. For a negative shock, the pass-through is lower for Midrigan, 2011 than for Golosov-Lucas, 2007 till a shock size of 4.6%. This asymmetry, as before, can be explained by the large asymmetric extensive margin effect of the model of Midrigan, 2011.

4 Empirical evidence

In this section we present empirical evidence for large inflation pass-through and quantitatively important asymmetry after positive and negative shocks. The experiment we use is two consecutive value-added tax changes in Hungary: a 5%-point decline followed by a 5%-point increase.

4.1 VAT-changes in Hungary

In 2006, in search for a simplification of the tax system, Hungarian authorities sequentially closed the gap between two different value-added tax rates. In January the top rate was decreased from 25% to 20%, and in September the lower rate was increased from 15% to 20%. We note that the tax increase of September could not be anticipated at the time of the tax decrease in January, as it was done by a new government elected in April. Also, as there were many products initially in both tax brackets, we have many affected products both in January and September.

We consider these VAT-changes are measurable and transparent cost push shocks directly influencing the gross prices of affected firms, which are the quoted prices in Hungary – differently from the US practice regarding sales tax, but similarly to most other European countries. This practice is also reinforced by a consumer protection law requiring that "consumers can not be forced to calculate prices in their head".[19] This cost push shock dominated the inflation effects during these months as the inflation targeting central bank has expressed in advance that it was not planning to respond to the direct effects of the tax shocks, because they only affect the price level and have only temporary effects on the measured inflation rate.

The tax changes had substantial direct effects on the consumer prices. Among the affected food products, the aggregate fraction of price-changing stores increased from 13.5% to 54.5% (on average of the two tax changes)[20], while the average absolute size of price changes dropped slightly from 9.9% to 8.9%. The tax shocks also had large but asymmetric inflation effects: the inflation pass-through of the positive tax shock was 98.9%, while it was 32.9% for the negative shock.

4.2 Data

To measure the effect of VAT-shocks, we use a data set of store-level quotes in Hungary between December 2001 and December 2006, collected by the Central Statistical Office for official CPI-calculations.[21] Among the many product categories, we focus on processed food items (128 different products, 98 affected by the tax increase and 30 by the tax decrease). The CPI-weight of these

[19] 1997.CLV. Law on Consumer Protection and 7/2001. (III. 29.) Ministry of Economy decree and its explanation.

[20] Gagnon (2009) documents similarly large frequency effect after large shocks in Mexico.

[21] For a detailed description of the data set, see Gabriel-Reiff (2010).

128 observed products is 16.1% (which means almost complete coverage *among processed food*, which has a total CPI-weight of 17.4%).

Each product in our data set is observed in approximately 100 stores each month, and as the Central Statistical Office tries to keep the store-product pairs unchanged over time, the number of item replacements and substitutions is small. Furthermore, in the analysis we focus on regular prices, rather than sales prices. The price collectors of the Central Statistical Office use a sales flag to identify sales prices (i.e. prices that are temporarily low, and have a "sales"label), and we use these flags to filter out sales prices in the first round. After this we also filter out any remaining price changes that are (1) at least 10 %, (2) and are completely reversed within 2 months.

4.3 Data moments

We have calibrated the model parameters in Section 2 to match some basic data moments, calculated from these data. During the calculations, we always calculated the moments at the product level, and then aggregated these with the CPI-weights of the products.[22] The matched moments were the following:

1. Trend inflation: 3.5% per year.
2. Frequency of price changes: 13.5% (monthly).
3. Average absolute size of non-zero price changes: 9.9%.
4. Interquartile range of the distribution of absolute size of price changes: 8.13%.
5. Kurtosis of the distribution of the size of price changes: 3.9768.

For calibrating the model parameters, we only used data from months when there were no tax changes.

To test the different models' predictions of large tax shocks, we have also calculated some additional moments from the months of tax changes:

1. Frequency of price changes during tax changes: 54.5% (average of the two tax changes).)
2. Average absolute size of non-zero price changes during tax changes: 8.9% (average of the two tax changes).
3. Inflation pass-through of the positive and negative tax shock: 98.9% and 32.9%.

[22] These CPI-weights are based on expenditures from household surveys.

4.4 Results

Table 2 contains information about our matched and unmatched moments. Given that we have the same number of parameters as the number of matched moments in each model variants, it is natural that we hit all the moments that we target.[23]

In terms of hitting non-matched moments, the Midrigan-model with leptokurtic shocks does remarkably well. First, we almost perfectly hit the large frequency increase observed during tax-changing months, reflecting the importance of the extensive margin already discussed in Section 3. The other models do not do nearly as well: the extensive margin in the Golosov-Lucas model does exist but it is quantitatively small, and there is no extensive margin in the Calvo model. Second, we the Midrigan-model also generates a decline in the average absolute size of price changes during the tax-changing months, reflecting many relatively small additional price changes (close to the size of the tax shock itself). This is because the peak of the desired price change distribution has become slightly outside the inaction region, and there is a big mass of firms that increases its price by only 5-10%. The Golosov-Lucas and the Calvo models have wrong predictions for the size of price changes during the months with tax changes (i.e. they predict that average sizes will be larger). Finally, the Midrigan-model also does quite well in generating substantial asymmetry in the inflation pass-through (although is slightly overestimates the pass-through in both cases). The asymmetry is also present in the Golosov-Lucas model, but it is not quantitatively important, and there is basically no asymmetry in the Calvo model.[24]

Table 2: Matched and unmatched moments

Matched moments	**Data**	**Model M**	**Model GL**	**Model C**
Frequency	0.1346	0.1346	0.1346	0.1346
Avg abs size	0.0991	0.0991	0.0991	0.0991
Iqr	0.0813	0.0817	*0.0344*	*0.1020*
Kurtosis	3.9768	3.9765	*1.7676*	*3.4827*
Unmatched moments	**Data**	**Model M**	**Model GL**	**Model C**
Frequency tax	0.5453	0.5383	0.2551	0.1346
Size tax	0.0887	0.0703	0.1038	0.1053
Infl eff −	0.3287	0.4794	0.5637	0.1393
Infl eff +	0.9886	1.1541	0.6056	0.1361

We view this empirical evidence of asymmetric pass-through of symmetric tax shocks in Hungary as a strong evidence in favor of state-dependent pricing

[23]Note that in the Golosov-Lucas and the Calvo models we have normally distributed productivity shocks, so we cannot hit the interquartile range and the kurtosis. Numbers in *italics* in the upper panel of the table are in fact non-matched moments.

[24]The numerically small asymmetry that we do observe is because of the asymmetric shap of the profit function.

models, as it cannot be explained by standard time-dependent pricing models.[25] We have also seen, however, that though asymmetry is present in the simple menu cost model of Golosov and Lucas (2007), as it does not have a strong extensive margin, it cannot account quantitatively for the strong asymmetry observed in data. We need some mechanism in the model to generate large extensive margin (a frequency jump from 13.5% to 54.5%!) in order to generate plausible levels of asymmetry. This mechanism is leptokurtic shocks in Midrigan's model.

We also believe that some alternative explanations of asymmetry cannot play a crucial role in explaining the asymmetric responses to Hungarian tax changes. First, consider an alternative state-dependent model assuming convex adjustment cost of price changes, like that of Rotemberg (1982). This model would also imply asymmetric inflation response, but with opposite sign: in an inflationary environment, the additional response of firms to positive shocks would be *smaller* than to a negative one, because the marginal cost of price increase (additional to the trend-inflation induced optimal positive change) would be higher. Moreover, a series of recent papers use search frictions to explain asymmetric price responses (Cabral and Fishman, 2010, and Yang and Ye, 2008). Their common key assumption, however, is that the marginal consumers are uninformed about the cost shocks faced by price setting firms, which is clearly not applicable to our case of VAT-shocks: these had easily measurable, widely publicized and uniform effects on all affected firms. Finally, the asymmetric inflation effect due to the asymmetric shape of the profit function (Devereux and Siu, 2007, Ellingsen et al, 2006) is in fact incorporated in our model, but numerical results showed that this type of asymmetry is negligible relative to the Ball-Mankiw-type asymmetry.

5 Robustness

In our baseline calibration, we have set the idiosyncratic persistence parameter to 0.5. Here we show sensitivity analysis of our results by changing this parameter to $\rho_A = 0.7$. We find that even though the assumption has quantitative effects, qualitatively the results stay the same. Table 3 shows the estimated parameters, the matched and the unmatched moments. The results show that with higher idiosyncratic persistence, the Midrigan, 2011 model requires lower p parameter (the proportion of 0 shocks), so lower kurtosis of the idiosyncratic shocks. With this calibration, the model still predicts higher frequency of price changing firms at the period of the tax shock than the Golosov-Lucas, 2007 calibration, but the difference is quantitatively smaller. The model is surprisingly good at hitting the pass-through for the negative shock, but it somewhat underestimates the pass-through for the negative shock. Still, the estimated asymmetry for the model of Midrigan, 2011 is much closer to those observed in the data than in the Golosov and Lucas, 2007 model.

[25] The large frequency response is another phenomenon which is clearly inconsistent with time-depemndent models.

Table 3: Calibration with $\rho_A = 0.7$

Parameters	**Data**	**Model M**	**Model GL**	**Model C**
ϕ	–	0.026	0.02	0
σ_A	–	0.047	0.050	0.366
p	–	0.89	0	0
κ	–	0.043	0	0
λ	–	–	–	0.1346
Matched moments	**Data**	**Model M**	**Model GL**	**Model C**
Frequency	0.1346	0.1346	0.1346	0.1346
Avg abs size	0.0991	0.0991	0.0991	0.0991
Iqr	0.0813	0.0813	*0.026*	*0.10*
Kurtosis	3.977	3.977	*1.59*	*3.48*
Unmatched moments	**Data**	**Model M**	**Model GL**	**Model C**
Frequency tax	0.545	0.28	0.24	0.135
Size tax	0.089	0.097	0.108	0.105
Infl eff –	0.329	0.337	0.55	0.1393
Infl eff +	0.989	0.737	0.61	0.1361

6 Conclusion

We have shown that the leptokurtic distributional assumption in the menu cost model of Midrigan, 2011 that implies higher real effects for monetary shocks than the standard Golosov and Lucas, 2007 model for small shocks and no inflation, actually implies lower real effects for large shocks or trend inflation. The reason is the extensive margin effect, that gets quantitatively important and highly non-linear with leptokurtic idiosyncratic shocks. We have also shown that even low trend inflation implies substantial inflation asymmetry for large shocks under the leptokurtic idiosyncratic shock assumption. The paper provided evidence from natural experiments of large value-added tax shocks in Hungary that strongly support the leptokurtic shock assumption and the aggregate predictions of the model of Midrigan, 2011.

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