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PRICE FLEXIBILITY AND OUTPUT VOLATILITY UNDER MENU COSTS

NAM T. VU
Miami University of Ohio

This paper studies the implications of price flexibility on output volatility under menu costs and finds price flexibility to be output-destabilizing under supply shocks, but not necessarily so under demand shocks. We illustrate that such a result hinges on the extent to which firms can adjust along both the intensive and the extensive margins, the latter of which is often absent in the literature.

Keywords: Price Flexibility, Output Volatility, Heterogeneous Agents, Menu Costs

1. INTRODUCTION

Is price flexibility output-destabilizing when firms are allowed to adjust along both the intensive and the extensive margins? The literature has studied this question using models in which the probability of price changes is exogenously determined, which implies that firms can choose the size (i.e., the intensive margin), but not necessarily the timing (i.e., the extensive margin) of price changes.[1] Allowing firms to decide both the timing and the size of price changes helps the model better capture firms' pricing behavior and, at the same time, significantly alters the mechanism through which changes in policy transmit in the economy. This feature, as emphasized by Caplin and Leahy (1991) and Golosov and Lucas (2007), allows menu cost models to capture extreme jumps or drops in inflation, and more generally, to capture abrupt changes in the state of the economy.[2]

This paper contributes to the literature by studying the implications of price flexibility on output volatility under menu costs, in which firms can choose both the timing and the size of price changes.[3] Under this setup, a typical price for an individual firm will stay the same for the majority of the time and may occasionally jump up or down, depending jointly on the state of the economy and the firm's draw of idiosyncratic shocks. As a result, an individual firm's decision to change prices depends not only on the joint distribution of its last period price and individual productivity but also on the firm's expectation of the future states of the economy.

Turning to more details, the economic environment consists of a representative household, a final good firm, and a continuum of intermediate goods firms.

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Address correspondence to: Nam T. Vu, Department of Economics, Miami University of Ohio, 800 E. High St., Oxford, OH 45056, USA. e-mail: vunt@miamioh.edu.

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Subject to both idiosyncratic and aggregate shocks, the intermediate goods firms can choose whether to change prices by paying a fixed menu cost, as long as the present discounted value of profits is higher than when not changing prices. Conversely, these firms can choose to keep the current prices if doing so is more preferable. This assumption follows the vast literature studying the implications of menu cost models (see, e.g., Caplin and Leahy (1991), Golosov and Lucas (2007), Gagnon (2009), and more recently Vavra (2014)).

Our main result is that whether output volatility increases with price flexibility depends largely on the nature of the shocks under menu costs. While this result, at first glance, seems similar to the one provided by the recent literature that assumes Calvo pricing, in which firms can only adjust along the intensive margin (see, e.g., Bhattarai et al. (2018)), the mechanisms and the conditions through which price flexibility is output-destabilizing are different under menu costs.

Specifically, under demand shocks, increases in price flexibility do not destabilize output. The intuition behind this result rests on the unique pricing mechanism of the intermediate firms under menu costs and, subsequently, on how shocks are transmitted to output via this pricing mechanism. In particular, in response to an unexpected change in the state of the economy, firms can respond immediately by adjusting prices and by paying a fixed menu cost. One implication of this setup, as noted by Golosov and Lucas (2007), is that price adjustments are typically implemented by firms whose prices are the furthest from the optimal prices. Consequently, this adjustment mechanism is reflected in a more stable response of aggregate price and, subsequently, more stable responses of both the real and the nominal interest rates. We find that this result is robust to varying the responsiveness of the central bank to changes in the state of the economy. In comparison, under Calvo pricing (i.e., firms can change the size, but not necessarily the timing of price changes), whether price flexibility is output-destabilizing under demand shocks depends on the responsiveness of the central bank, as carefully documented by Bhattarai et al. (2018).

Under supply shocks, we find price flexibility to be output-destabilizing. Intuitively, while firms are able to respond immediately to a supply shock by paying a fixed menu cost, a decrease in this cost (i.e., more flexible prices) implies a more volatile response of aggregate price since, unlike demand shocks, supply shocks both shift the level and increase the dispersion of the price distribution. When the central bank responds aggressively to changes in inflation, increases in price flexibility amplify how output decreases in response to a positive supply shock. When the central bank does not respond aggressively, price flexibility amplifies the reduction of output following the same shock. All in all, regardless of the responsiveness of the nominal interest rate, we find output volatility to increase as the cost of changing prices becomes smaller.

To illustrate these contrasting patterns between demand-side and supply-side shocks, we allow firms in the model to be subject to an aggregate supply shock and an aggregate demand shock, in addition to their draws of idiosyncratic shocks. We next calibrate the model to match Japanese micro-price data and solve the model globally. To check the sensitivity of our main results, we examine the model's predictions when the nominal interest rate is unresponsive, when the target inflation rate is high, when monetary policy is largely contractionary, and when consumers are more risk-averse. We also compare our model's implications with an identically calibrated Calvo version of the model. Last but not least, we also explore the welfare implications of the output-destabilizing nature of price flexibility in menu costs.

This paper is related to, first and foremost, the literatures that study how price flexibility (see, e.g., Eggertsson (2011) and more recently Bhattarai et al. (2018)) and wage flexibility (see, e.g., Galí (2013) and Galí and Monacelli (2016)) can be output-destabilizing. Commonly assumed in this literature is the pricing mechanism in which firms' timing of price changes is exogenously determined by a fixed probability. As noted by Golosov and Lucas (2007) and Gagnon (2009), allowing firms to choose both the timing and the size of price changes can help the model better match with micro-price evidence and, at the same time, can result in significantly different implications on output response dynamics. One source of the novelty of this paper, therefore, is to assess the output-destabilizing nature of price flexibility under menu costs, in which firms can decide both the timing and the size of price changes. Naturally, this paper also belongs to a large and growing literature that studies the theoretical implications of menu costs (see, e.g., Golosov and Lucas (2007), Nakamura and Steinsson (2010), and Vavra (2014)) as well as the implications of menu costs in micro-price data (see, e.g., Gagnon (2009) and Bils and Klenow (2004)).

This paper proceeds as follows. Section 2 describes the model. Section 3 takes the model to the data, calibrating it to key features of Japanese data. Section 4 presents and discusses the intuitions behind the main results. We consider a battery of robustness checks to these results in Section 5. Section 6 concludes.

2. MODEL

The economic environment consists of a representative household and a final good firm, the latter of which bundles all goods from the immediate good firms and sells to customers. In every period, each immediate firm is presented with the choice of either changing or keeping its current price. If the firm decides to change its price, it will have to pay a fixed menu cost in exchange for the ability to choose a price that maximizes the present discounted value of profits.

2.1. Households

The household consumes goods and works at a prevailing wage W_t. In particular, the household maximizes

$$E_0 \sum_{t=0}^{\infty} \beta^t U\left(C_t, N_t\right),$$

subject to the budget constraint

$$P_tC_t + Q_{t,t+1}D_{t+1} \leq D_t + W_tN_t + \int_0^1 \Pi_t\,(j)\,dj + T_t.$$

In terms of notation, N_t denotes the amount of labor provided at a prevailing wage W_t; $\int_0^1 \Pi_t(j)dj$ denotes the total profits transferred to the households by all firms; T_t denotes transfers from the government; D_{t+1} denotes the quantity of risk-free discounted bonds, purchased at time t and will pay one unit of money at time $t+1$.

The utility function of the consumer follows

$$U\,(C_t, N_t) \equiv \frac{C_t^{1-\sigma}}{1-\sigma} - \psi\frac{N_t^{1+\varphi}}{1+\varphi},$$

in which ψ controls the disutility of working, σ is a parameter that dictates the degree of relative risk aversion, and φ is the inverse of the Frisch elasticity of labor supply. The price of the discounted nominal bonds D_{t+1} is $Q_{t,t+1}$. The first order conditions for consumption, labor, and bonds write

$$\frac{W_t}{P_t} = -\frac{U_{N,t}}{U_{C,t}}, \tag{1}$$

$$Q_{t,t+1} = \beta E_t\left[\frac{U_{C,t+1}}{U_{C,t}}\frac{P_t}{P_{t+1}}\right]. \tag{2}$$

Here (1) describes the labor supply while (2) describes the relationship between the price of bonds and the time path of consumption. For convenience, we define the nominal interest rate R_t as $1/Q_{t,t+1}$; therefore, the inter-temporal condition for the representative consumer (i.e., (2)) writes

$$1 = \beta E_t\left[R_t\frac{U_{C,t+1}}{U_{C,t}}\frac{P_t}{P_{t+1}}\right]. \tag{3}$$

2.2. Firms and Pricing Decisions

There are two types of firms: a continuum of intermediate good firms and a final good firm. The final good firm bundles goods produced by the intermediate good firms to meet aggregate demand Y_t. The cost minimization problem for the final good firm yields the standard demand for goods produced by intermediate firm j as follows:

$$Y_t(j) = \left(\frac{P_t(j)}{P_t}\right)^{-\theta} Y_t.$$

A continuum of intermediate good firms use labor as the only production factor to meet input demand of the final good firm. In particular, each intermediate firm j produces using the following technology:

$$Y_t(j) = Z_tA_t\,(j)\,N_t(j),$$

in which $Y_t(j)$ denotes the output of firm j in period t, $A_t\,(j)$ denotes the draw of technology of firm j, Z_t denotes an aggregate technology that affects all firms, and $N_t\,(j)$ denotes the quantity of labor firm j demands for production. Individual technology of firm j follows a standard (log) normal AR(1) process of the form

$$\log\left(A_t\,(j)\right) = \rho_A \log\left(A_{t-1}\,(j)\right) + \varepsilon_t\,(j)\,, \tag{4}$$

in which $\varepsilon_t\,(j)$ is an idiosyncratic i.i.d. productivity shock that follows $N\left(0, \sigma_A^2\right)$. Aggregate technology Z_t that affects all firms also follows a standard (log) normal AR(1) process of the form

$$\log\left(Z_t\right) = \rho_Z \log\left(Z_{t-1}\right) + \varepsilon_t^Z,$$

in which ε_t^Z is an aggregate i.i.d. productivity shock that is normally distributed with mean zero and a finite variance (σ_Z^2).

Each intermediate firm j maximizes its stream of discounted profits at time t as follows:

$$E_t \sum_{k=0}^{\infty} Q_{t,t+k} \Pi_{t+k}\,(j)\,, \tag{5}$$

and the firm's profit in period t is given by

$$\Pi_t\,(j) = P_t\,(j)\,Y_t\,(j) - W_t N_t\,(j) - \chi \Gamma_t\,(j)\,W_t, \tag{6}$$

in which $\Gamma_t\,(j)$ is an indicator function which takes the value of 1 if intermediate firm j decides to change the price it offers to the final good firm and 0 otherwise.

Intermediate good firm j first chooses the amount of labor to employ given the demand by the final good firm and forms its decision on pricing. In the latter phase, the firm must first decide whether to change its price at time t (the extensive margin) and then by how much (the intensive margin). It changes prices only if the expected discounted stream of profits when doing so (V^C) is greater than the expected discounted stream of profits when keeping the price it offered in the previous period (V^K). Following the literature on menu costs (see, e.g., Gagnon (2009)), we assume if an intermediate firm decides to change its price at period t, it has to pay a menu cost χW_t equal to a fraction χ of the prevailing wage W_t.

Here intermediate firm j's decision whether to change prices is endogenous because it depends on the draw of productivity the firm receives at time t, and on the draws of the aggregate shocks (i.e., the government spending shock and the aggregate TFP shock). The pricing decision by firm j at time t is given by

$$p_t\,(j) = \begin{cases} p_{t-1}\,(j) & \text{if} \quad V^C\left(p_t^c\,(j)\,; \bar{\Omega}_t, A_t\,(j)\right) \le V^K\left(p_{t-1}\,(j)\,; \bar{\Omega}_t, A_t\,(j)\right) \\ p_t^c\,(j) & \text{if} \quad V^C\left(p_t^c\,(j)\,; \bar{\Omega}_t, A_t\,(j)\right) > V^K\left(p_{t-1}\,(j)\,; \bar{\Omega}_t, A_t\,(j)\right) \end{cases}, \tag{7}$$

in which $p_t\,(j) \equiv \dfrac{P_t\,(j)}{P_{t-1}\,(j)}$ denotes the real price choice by intermediate firm j at time t; $\bar{\Omega}_t$ is a set of the aggregate states of the economy; $p_t^c\,(j) \equiv \arg\max_{p_t(j)} \left\{V^C\left(p_t\,(j)\,; \bar{\Omega}_t, A_t\,(j)\right)\right\}$ denotes the optimal price, conditional on the decision to change price by intermediate firm j. Here $V^C(.)$ is the value function when intermediate firm j changes its currently offered price, conditional on its draws of idiosyncratic productivity and aggregate shocks at time t. Similarly, $V^K(.)$ is the value function when intermediate firm j decides to keep the price it offered at period $t-1$, in which case the firm is not required to pay any menu cost. Equivalently, in terms of notation in (6), $\Gamma_t(j)$ is equal to 0 when $V^C\left(p_t^c(j);\bar{\Omega}_t, A_t(j)\right) \leq V^K\left(p_{t-1}(j);\bar{\Omega}_t, A_t(j)\right)$ and is equal to 1 otherwise.

We thus can write the problem for intermediate firm j recursively as follows:

$$\begin{aligned} V^C\left(p_t^c(j);\bar{\Omega}_t, A_t(j)\right) &\equiv \max_{p(j)} \Big\{ \Pi_t^C\left(p(j);A_t(j),\bar{\Omega}_t\right) + E\left\{Q_{t,t+1}\right\} \\ &\qquad\qquad V\left(p_{t+1}(j);\bar{\Omega}_{t+1}, A_{t+1}(j)\right) \Big\} \\ V^K\left(p_{t-1}(j);\bar{\Omega}_t, A_t(j)\right) &\equiv \Pi_t^K\left(p_{t-1}(j);A_t(j),\bar{\Omega}_t\right) + E\left\{Q_{t,t+1}\right\} \\ &\qquad\qquad V\left(p_{t+1}(j);\bar{\Omega}_{t+1}, A_{t+1}(j)\right) \qquad \textbf{(8)} \\ V\left(p_t(j);\bar{\Omega}_t, A_t(j)\right) &\equiv \max\left\{V^C\left(p_t^c(j);\bar{\Omega}_t, A_t(j)\right), V^K\left(p_{t-1}(j);\bar{\Omega}_t, A_t(j)\right)\right\}, \end{aligned}$$

in which V^C and V^K denote the corresponding value functions when intermediate firm j decides to change and to keep its current price, respectively. All in all, in each period, intermediate firm j is subject to three shocks: (1) its draw of idiosyncratic shock via $A_t(j)$, (2) an aggregate supply shock via Z_t, and (3) an aggregate demand shock via G_t. For the rest of the paper, we refer to the aggregate supply shock simply as supply shock and the aggregate demand shock simply as demand shock.

2.3. The Nominal Interest Rate

While not necessarily central to our analysis, the model also allows for an endogenous transition in and out of the zero lower bound (ZLB) to account for the recent near-zero nominal interest rate experience of Japan since the 1990s and of many economies during and after the Great Recession.[4] To that end, the nominal interest rate is constrained by a lower bound at zero. In particular, the nominal interest rate, when not binding, is

$$\tilde{R}_t = \bar{R}E_t\left[\left(\frac{Y_t}{\bar{Y}}\right)^{\phi_y}\left(\frac{1+\pi_t}{1+\bar{\pi}}\right)^{\phi_\pi}\right], \qquad \textbf{(9)}$$

in which $\bar{\pi}$ denotes the target inflation rate; ϕ_y and ϕ_π dictate how monetary policy reacts to fluctuations in output and inflation gaps, respectively. Under the ZLB occasionally binding constraint, the nominal interest rate thus writes

$$R_t = \max\left(\tilde{R}_t, 1\right),$$

in which $\tilde{R}_t$ denotes the unconstrained nominal interest rate and R_t denotes the constrained one.

2.4. Market Clearing Conditions and Government Spending

Production in the economy must meet the demand of consumption and government spending. In particular,

$$Y_t = G_t + C_t.$$

The labor market must also be clear; that is, $N_t = \int_0^1 N_t\,(j)\,dj$, or $N_t = \frac{Y_t}{A_t}\vartheta_t$, in which $\vartheta_t = \int_0^1 \left(\frac{P_t(j)}{P_t}\right)^{-\theta} dj$ denotes the degree of price dispersion. Since the firms are subject to both idiosyncratic and common productivity shocks, A_t aggregates $Z_t A_t\,(j)$ across all firms. Government spending is an AR(1) process (in log) as follows:

$$\log(G_t) = (1-\rho_G)\log(\bar{G}) + \rho_G \log(G_{t-1}) + \varepsilon_t^G, \tag{10}$$

in which ε_t^G is i.i.d. and follows $N\left(0, \sigma_G^2\right)$. Balanced budget by the authority requires that $P_t G_t = T_t$ in each period t.

3. MODEL CALIBRATION AND SOLUTION

We next present the set of parameters chosen for the model, as well as the solution method.

3.1. Calibration

Median Frequency and Average Size of Price Changes. We use the "Report on the Retail Price Survey" published by the Statistics Bureau, Management and Coordination Agency of Japan. The dataset is a tridimensional (time, locations, and goods) panel of monthly Japanese consumer prices from 1975 to 1999, covering 65 goods and more than 70 cities.[5] Table A.2 in the Online Appendix presents a list of cities covered and the number of goods, along with the corresponding average price change (annualized). Here we note that the dataset exhibits a strong consistency in terms of the number of goods across cities.

We next obtain the frequency and the average size of price changes as follows. For every unique combination of city and good, we calculate the number of price changes from one month to another over the entire span of the dataset. We then divide this number by the number of periods to arrive at the frequency of price changes for each combination of city and good. Next, we take the mean and median across all combinations of cities and goods to arrive at the corresponding statistics for the size and the frequency of price changes.

Overall, price changes are relatively infrequent. Across all cities, the median and the average frequency of prices changes are around 3.7% and 3.5%, respectively. These numbers are smaller than equivalent values found in the US data, in which the median frequency of price changes is approximately 8%.[6] Across all goods, the average size of price changes is 3.4%.[7] As noted by Golosov and

Lucas (2007), to generate an average size of price changes that is congruent with microdata requires the innovation to the idiosyncratic productivity process to have a relatively large standard deviation. In our context, the standard deviation of the innovation to productivity σ_A is set to 0.0312 for the model to replicate an average size of price changes of around 3.4%, which is consistent with the Japanese data from the "Report on the Retail Price Survey." The markup for the fixed menu cost χ (as a fraction of real wage) is set to 0.124 so that the frequency of price change $1-\gamma$ implied by the model matches the frequency of price change from micro-price evidence.[8]

Monetary Rule. We next select parameters governing the monetary rule. While the literature that estimates these parameters for Japan differs significantly in terms of methods, most papers appear to converge on a large value for the coefficient on the inflation gap (ϕ_π) and a relatively small value for the coefficient on the output gap (ϕ_y). For example, Domenico (2006) finds ϕ_π to be between 1.3 and 3.2 and ϕ_y to be statistically indistinguishable from 0. Most recently, using censored quantile regressions to account for the prolonged zero interest rate periods, Chen and Kashiwagi (2017) and Chevapatrakul et al. (2009) find the range of ϕ_π to be between 1.41 and 3.2. While documenting a wide range for the values of the coefficient on the inflation gap (ϕ_π), these papers all find the coefficient for the output gap (ϕ_y) to be statistically insignificant from zero. Following this literature, we use 0 and 1.5 for ϕ_y and ϕ_π, respectively. The inflation target $\bar{\pi}$ is set to be 2% (annualized) to reflect the official inflation expectation of the Bank of Japan (≈1.5%–2%—2008–2014, *Outlook for Economic Activity and Prices*).

Degree of Relative Risk Aversion. Empirical estimates for the degree of relative risk aversion from the financial economics literature are typically larger than unity (see, e.g., Mehra and Prescott (1985), Szpiro (1986), Kocherlakota (1996), Barsky et al. (1997), and Kaplow (2005)). On the other hand, the same estimates from the labor and mortality risk premium literature range from 0.5 to 0.6, with an upper bound of slightly less than unity (see, e.g., Viscusi and Evans (1990) and Viscusi and Aldy (2003)) or are centered around unity (see, e.g., Chetty (2006)). Because σ varies between 0.5 (Viscusi and Aldy (2003)) and 5 (Barsky et al. (1997)) across these two strands of literature, we set σ to be 3 to stay between these two extremes.

Other Parameters. The subjective discount factor $\beta = 0.987^{1/12}$ is chosen so that the implied steady-state nominal interest rate is consistent with Japan's average nominal interest rate from 1990:M1 to 2015:M3 (1.24%).[9] The inverse of the Frisch elasticity of labor φ is 0, which is similar to those in the menu cost literature (e.g., Nakamura and Steinsson (2010) and Golosov and Lucas (2007)). As carefully documented by Golosov and Lucas (2007), setting the inverse of the Frisch elasticity of labor φ to 0 allows menu cost models to remain tractable. The parameter ψ that dictates the disutility of labor is set so that the flexible price steady-state value of hour is 1/3, following Nakamura and Steinsson (2010).

One difficulty of selecting the elasticity of substitution across different varieties of goods θ for Japan is that there has not been any attempt, to our best knowledge, to estimate this parameter using scanner data on a similar scale as the ones using the US data. We set θ to 3 to be consistent with earlier studies using US micro-price data. For example, Nevo (2001) estimates the parameter to fall within a range from 1.4 to 2.1, Midrigan (2007) uses $\theta = 3$, and Nakamura and Steinsson (2010) use $\theta = 4$. Following Fueki et al. (2016) and Iwata (2009) who estimate a DSGE model for Japan using Bayesian methods, we set the persistence parameters for both the aggregate (ρ_Z) and idiosyncratic (ρ_A) TFP shock processes to 0.92.

We next turn to the parameters governing the government spending process, specifically ρ_G and $\bar{G}$. Despite the abundance of papers that estimate the government spending process for the USA, similar estimates for Japan are far and few between. Iwata (2009) estimates a New Keynesian DSGE model using Bayesian methods to Japanese data from 1980 to 1998 and finds the estimated mode of ρ_G to be 0.74. Most recently, Fueki et al. (2016) find this value to be 0.93 using another estimated DSGE model. For our baseline specification, we choose ρ_G to be 0.8 to stay between these two extremes. Turning to the steady-state government spending, we choose the value of $\bar{G}$ so that the flexible price steady-state ratio of government spending to output $s^g \equiv \bar{G}/\bar{Y}$ is 0.176. The 0.176 value corresponds to the average empirical value of the ratio between government spending and output from 1990:Q1 to 2015:Q4.[10] Table 1 summarizes all the parameters.

3.2. Model Solution

We use global methods to solve for the policy function to retain full nonlinearities of the model by discretization. In particular, we initiate the state space around the model's flexible price steady-state values and use the Tauchen (1986) method to discretize the AR(1) processes for productivity and government spending with approximately 5.4 million total grid points.[11] As noted by Knotek and Terry (2008), discretization can be just accurate as collocation methods when the number of grid points is reasonably high.[12]

Given the max rule for the nominal interest rate, intermediate firms still need information that reflects other firms' pricing choices, which are not available at the time the decision is rendered. To get around this problem, following Krusell and Smith (1998), we posit that the intermediate firms forecast the state of the economy in the next period using a set of aggregate laws of motion $m^{'} = f\,(m; B, \xi)$, in which ξ denotes the set of state variables and B denotes the set of estimates for a selected numbers of forecasting moments. We find the following moment μ_P to be able to capture the price distribution well:

$$\mu_P = \int_0^1 \log\left(\frac{p_j'}{p_j''}\right) dj, \qquad \textbf{(11)}$$

in which p_j' and p_j'' denote previous pricing decisions of firm j.[13]

TABLE 1. Summary of parameters

Par.	Value	Notes	Description
β	$0.987^{1/12}$	Japanese nominal interest rate (1990–2015). St Louis FRED	Subjective discount factor
θ	3	Nakamura and Steinsson (2010)	Elasticity of sub. across variety
ψ	3	Nakamura and Steinsson (2010)	Labor disutility
σ	3	Kocherlakota (1996), Barsky et al. (1997), Kaplow (2005), among others	Degree of relative risk aversion
φ	0	Nakamura and Steinsson (2010), Golosov and Lucas (2007)	Inverse of Frisch elasticity
$\rho_A = \rho_Z$	0.92	Fueki et al. (2016) and Iwata (2009)	Persistence of productivity
ρ_G	0.8	Fueki et al. (2016) and Iwata (2009)	Persistence of gov. spending
$[\phi_y; \phi_\pi]$	[0; 1.5]	Domenico (2006)	Monetary rule parameters
$\bar{\pi}$	2%	*Outlook for Economic Activity and Prices*	Target inflation rate (Annualized)
$s^g \equiv \bar{G}/\bar{Y}$	0.176	St. Louis FRED Data (1990:Q1 to 2015:Q4)	Gov. spending over output
χ	0.124	Report on the Retail Price Survey	Menu-cost markups

We first make a guess of $\mu_P^{'}$ and solve for the policy function using value function iterations. We then simulate the model by generating a random sample of stochastic shocks using a large number of firms ($N = 1000$) and periods ($T = 1000$) to obtain a new estimate of the distribution of idiosyncratic decision $\mu_P^{''}$. Following Maliar et al. (2010), we update the next optimal guess μ_P for this distribution using the following adjustment:

$$\mu_P = \lambda^s \mu_P' + (1 - \lambda^s)\, \mu_P'',$$

in which λ^s is a smoothing parameter.[14] We then keep iterating until the aggregate law of motion μ_P converges. To improve the accuracy of the policy function, we also use cubic splines interpolation when the differences between iterations are sufficiently small. Overall, our solution involves finding a pair of policy and value functions that satisfy (i) the fixed-point problem (8) and (ii) the aggregate law of motion (11).[15]

4. MAIN RESULTS

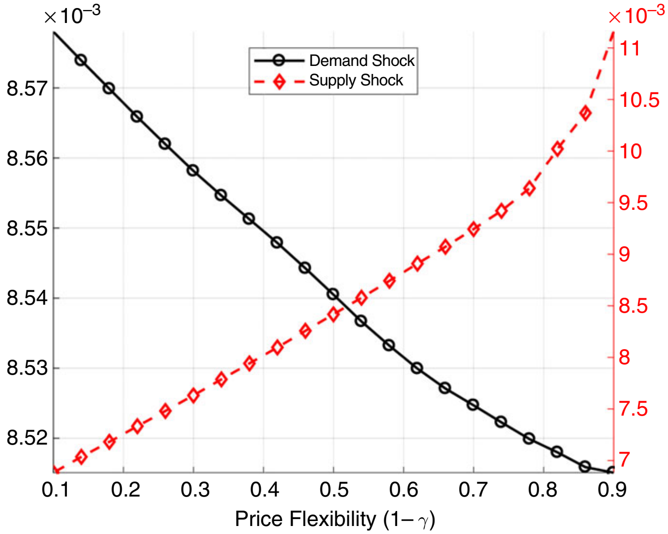
4.1. Setup

We examine how price flexibility destabilizes output by varying the size of the menu costs χ and reporting the corresponding statistics from the simulated model.[16] In doing so, we isolate the sources of the shocks to the model under two cases: demand-driven and supply-driven. Our motivation for focusing on these two cases follows in part from a recent literature, which shows that the extent to which increases in price flexibility are output-destabilizing under time-dependent pricing depends significantly on the source of the shocks (see, e.g., Bhattarai et al. (2018)).

To single out the effects of price flexibility under demand shocks, we shut down the aggregate TFP shock Z_t while setting the standard deviation of the aggregate government spending shock $\sigma_G = 0.02$. Similarly, to single out such effects under supply shocks, we shut down the government spending shock and set the standard deviation of the aggregate TFP shock $\sigma_Z = 0.02$. Across these two settings, we keep the rest of the parameters as in Section 3. In all of our exercises, we use solid lines with circle markers and dashed lines with diamond markers to illustrate the model implications under demand shocks and under supply shocks, respectively. To generate our results, we simulate the model with 1000 firms and 1000 periods. For the rest of the paper, the menu cost model presented in Section 2 is referred to as the benchmark model.

4.2. Output Volatility and Price Flexibility under Menu Costs

Our key result is that extent to which price flexibility destabilizes output depends largely on the source of the shocks under menu costs. While this conclusion, on the surface, seems almost identical to the one implied by Calvo/time-dependent models (see, e.g., Bhattarai et al. (2018)), the mechanisms and the conditions



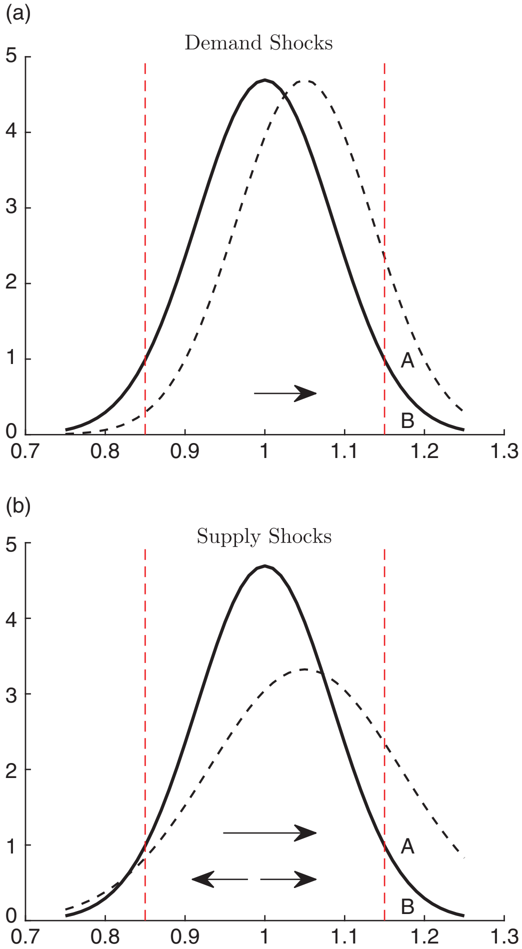
Notes. We simulate the model for 1000 periods and 1000 firms and calculate the corresponding statistics. In each round, we alter the menu cost χ such that the implied price flexibility $(1-\gamma)$ varies as in the horizontal axis. Output volatility is defined as the standard deviation of output (in logarithm) over time, averaged out over 1000 samples. We plot output volatility generated when shutting down the aggregate supply shock (to isolate the effects of increases in price flexibility under demand shocks) using the solid line with circle markers. Likewise, we shut down the aggregate demand shock and report the corresponding output volatility using the dashed line with diamond markers. Our calibration follows Section 3. The average frequency of ZLB events from our simulation under this baseline calibration across all degrees of implied price rigidity (γ) is 7.53%.

FIGURE 1. Output volatility and price flexibility.

under which price flexibility destabilizes output differ across the two models and critically hinge on the difference in the price responses of the firms.

Turning to more details, we plot output volatility against the implied price flexibility under menu costs in Figure 1. Under demand shocks, increases in price flexibility do not destabilize output, as evidenced by the negative relationship between price flexibility and output volatility in Figure 1. The intuition behind this result rests on the pricing mechanism of the intermediate firms under menu costs and, subsequently, on how the shocks are transmitted to output via this pricing mechanism. In particular, conditional on an unexpected change in the state of the economy, firms can respond immediately by adjusting prices and by paying the fixed menu costs. One implication of this setup, as noted by Golosov and Lucas (2007), is that price adjustments are typically implemented by firms whose prices are the furthest from the optimal prices.

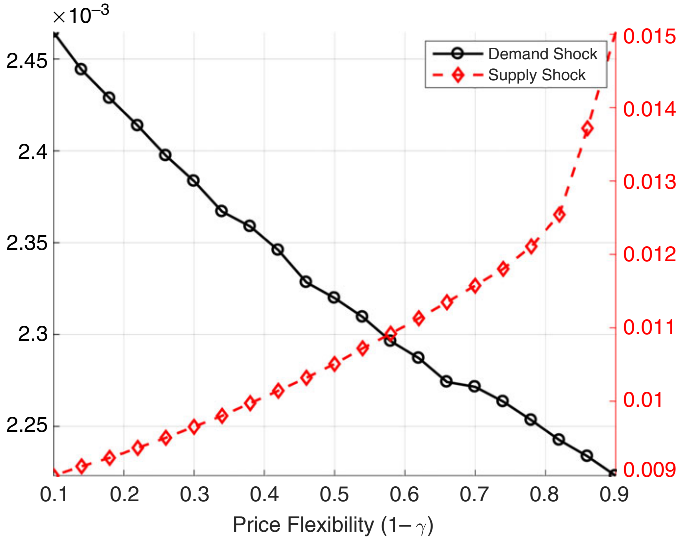
We illustrate this feature in Figure 2, which plots a stylized distribution of the ratio of a firm's price at the beginning of time t to its optimal price, or the distance between the two.[17] A value of 1 here implies that the firm's current price is identical to its optimal price. The vertical lines encompass the optimal price distance



Notes. This figure plots the stylized distribution of prices relative to the desired prices under a positive demand shock and a positive supply shock. The vertical lines denote the optimal bands. The solid bell curves denote the ex-ante distribution and the dotted bell curves denote the ex-post distribution.

FIGURE 2. Price responses under demand and supply shocks—an illustration.

band, in the sense that firms whose prices are outside of this optimal band would need to adjust their prices (i.e., the *B* area in Figure 2) and pay the menu cost. An aggregate demand shock pushes the whole distribution (the solid curve) to either the left or the right (the dashed curve), effectively creating a larger share of sub-optimal prices that would require adjustments (i.e., the additional *A* area in Figure 2).[18] In comparison, under Calvo/time-dependent pricing, firms across the whole price distribution are randomly selected to change their prices, regardless of the distance between the firm's ex-ante price and the optimal price.



Notes. This figure plots the standard deviation of the real interest rate when the model is either demand-shock or supply-shock driven. In particular, we plot the interest rate volatility generated when shutting down the aggregate supply shock (to isolate the effects of increases in price flexibility under demand shocks) using the solid line with circle markers. Likewise, we shut down the aggregate demand shock and report the corresponding output volatility using the dashed line with diamond markers. To generate these interest rate series, we simulate the model for 1000 periods and 1000 firms and calculate the corresponding statistics. In each round, we alter the menu cost χ such that the implied price flexibility $(1-\gamma)$ varies as in the horizontal axis. Our calibration follows Section 3.

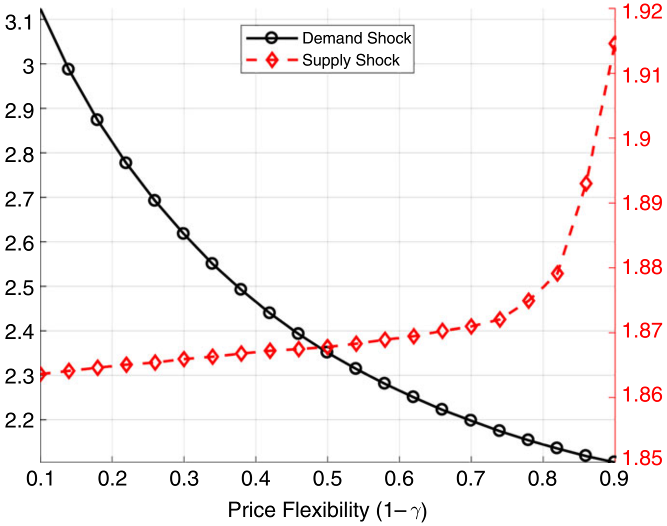
FIGURE 3. Real interest rate volatility.

Conditional on having the same aggregate demand shock, more firms are able to adjust the price ratio to unity instantly in Figure 2 (i.e., so that their new prices are identical to the optimal prices) under higher price flexibility. This price adjustment mechanism is thus reflected in more stable movements of aggregate price and, subsequently, more stable movements of both the real and the nominal interest rates. Intuitively, when it is less costly to change prices, firms do not need to preemptively adjust in response to a change in aggregate demand, which results in a less volatile response of aggregate price. Subsequently, this implies a more stable response from the central bank and, hence, a more subdued response of the real interest rate. Such a mechanism under menu costs differs from the more common Calvo pricing mechanism (the implications of which shall be verified in the next section), in which firms need to preemptively adjust along the intensive margin to account for the possibility of not being able to change their prices in the upcoming periods (i.e., the lack of the extensive margin). Indeed, as evidenced in Figure 3, under demand shocks, our benchmark menu cost model confirms that increases in implied price flexibility do not necessarily translate into more volatile responses of the real interest rate. Since responses of aggregate output are directly related to movements in the real interest rate, more stable realizations of the real interest rate imply lower output volatility as prices become more flexible.

Under supply shocks, price flexibility destabilizes output, as evidenced by the increases in output volatility with higher price flexibility (Figure 1). Intuitively, when the central bank responds aggressively to changes in inflation, increases in price flexibility amplify how output decreases in response to a positive supply shock. When the central bank does not respond aggressively, price flexibility amplifies the reduction of output following the same shock. Overall, price flexibility destabilizes output regardless of how responsive the central bank is. In our baseline calibration, the central bank is relatively responsive to changes in inflation since $\phi_\pi = 1.5$. We shall later check the sensitivity of this result with an alternative value of ϕ_π in Section 5.

In stark contrast with the demand-shock case, a decrease in the menu cost (i.e., an increase in implied price flexibility) does not necessarily translate into more stable responses of aggregate price since an aggregate supply shock both shifts and increases the dispersion of the distribution of the ratio of the firms' prices to their optimal prices, as illustrated in Figure 2. To see why this is the case, consider firm j's marginal cost $W_t / (Z_t A_t(j))$, absent of the menu cost. Under a positive shock to Z_t, a negative (or positive) shock to $A_t(j)$ is amplified by this Z_t shock in either direction. This means that while a reduction in the cost of changing prices allows more firms to adjust instantly, it also amplifies the dispersion of this price distribution. Because of the history-dependent nature of the firms' pricing mechanism along the extensive margin, the combination of these two channels amplifies the firms' price responses under higher price flexibility. In comparison, since demand shocks shift, but do not directly increase the dispersion of, the price distribution, price flexibility is not necessarily output-destabilizing as more firms can adjust instantly, which is consistent with the result presented in Figure 1.

To verify how such intuition under these two shocks materializes in our model, we plot, in Figure 4, the kurtosis of the price change distribution across a wide range of implied flexibility.[19] Under supply shocks, as we increase price flexibility, the distribution of price changes becomes heavier-tailed, as evidenced by the larger values of kurtosis.[20] One implication of this heavier-tail price distribution is that increases in price flexibility can amplify the responses of both inflation and the nominal interest rate, which lead to more volatile responses of the real interest rate, as evidenced from Figure 3. Such an increase in interest rate volatility translates into higher output volatility under supply shocks as price becomes more flexible. Under demand shocks, on the other hand, it is reassuring to find the kurtosis of the price distribution decreases with price flexibility. Specifically, a decrease in kurtosis implies a lighter-tailed price distribution in the sense that fewer firms need to change prices, which is consistent with the result that price flexibility is not necessarily output-destabilizing in Figure 1.

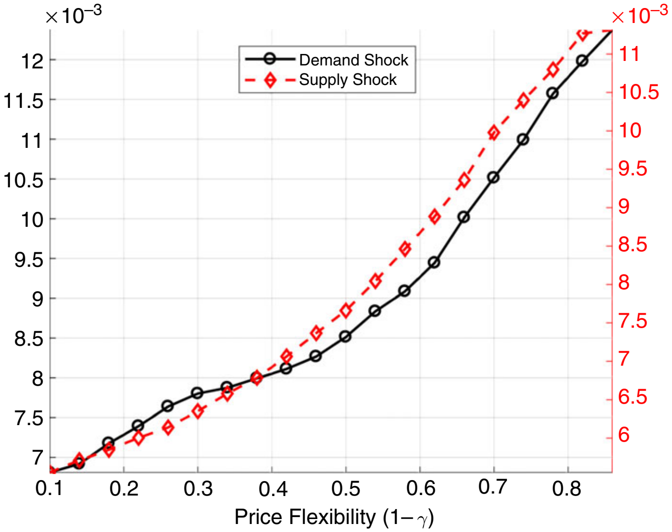


Notes. This figure plots the Kurtosis of the price change distribution when the model is either demand-shock or supply-shock driven. In particular, we plot this statistic generated when shutting down the aggregate supply shock (to isolate the effects of increases in price flexibility under demand shocks) using the solid line with circle markers. Likewise, we shut down the aggregate demand shock and report the corresponding values using the dashed line with diamond markers. To generate these interest rate series, we simulate the model for 1000 periods and 1000 firms and calculate the corresponding statistics. In each round, we alter the menu cost χ such that the implied price flexibility $(1-\gamma)$ varies as in the horizontal axis. Our calibration follows Section 3.

FIGURE 4. Kurtosis of price distribution.

4.3. Calvo Pricing versus Menu Costs

So far we have illustrated that under menu costs, price flexibility is output-destabilizing for supply shocks, but not necessarily so for demand shocks. These contrasting patterns hinge on the unique pricing mechanism under menu costs, in which firms can adjust along both the extensive and the intensive margins. In this section, we compare these results under menu costs with those generated under an identically calibrated time-dependent version of the model. Specifically, we replace the menu cost assumption in the benchmark model with a pricing assumption à la Calvo (1983), in which firms can only reset prices with a probability of $1-\gamma$, independent of previous adjustments. In other words, in each period, a fraction γ of firms may not reset prices and therefore are stuck with the prices they had at the beginning of the period. With the exception of the firms' pricing mechanism, we keep all other elements of the model intact and follow the calibration strategy outlined in Section 3. We solve this Calvo version of the model globally and vary the degree of price rigidity γ such that $1-\gamma$ corresponds to the implied price flexibility under our menu cost version of the model.



Notes. This figure plots the standard deviation of output (i.e., output volatility) under an identically calibrated Calvo version of the model that is either demand-shock or supply-shock driven. This Calvo version of the model is also solved globally using discretization. In particular, we plot output volatility generated when shutting down the aggregate supply shock (to isolate the effects of increases in price flexibility under demand shocks) using the solid line with circle markers. Likewise, we shut down the aggregate demand shock and report the corresponding output volatility using the dashed line with diamond markers. In each round, we alter the Calvo price stickiness γ such that the implied price flexibility $(1-\gamma)$ varies as in the horizontal axis.

FIGURE 5. Output volatility and price flexibility under Calvo pricing.

Figure 5 plots output volatility across various degrees of price flexibility $(1-\gamma)$ under the Calvo version of the model. We find increases in price flexibility to be largely output-destabilizing under both demand and supply shocks. Under supply shocks, even though price flexibility is output-destabilizing under both the menu cost and the Calvo versions of the model, the mechanism through which this happens differs across the two versions. In particular, under menu costs, increases in price flexibility lead to increased dispersion of the price change distribution as discussed in the previous section. Even though firms find it less expensive to adjust prices, given the history-dependent nature of menu cost models, such increases in price dispersion dominate the instant adjustment effects under menu costs and therefore imply an overall increase in output volatility. Under the Calvo version of the model, a positive supply shock, for example, can impact output in either direction, depending on the responsiveness of the central bank. Increases in price flexibility imply higher price dispersion, prompting larger responses in aggregate variables in either direction, which suggests that price flexibility is always output-destabilizing, as noted by Bhattarai et al. (2018).

Unlike under supply shocks, we find rather contrasting output-destabilizing patterns of price flexibility under the two versions of the model under demand shocks. In particular, while price flexibility is output-destabilizing under a similarly calibrated Calvo version of the model, it is not necessarily the case under the menu cost version. Under Calvo pricing, since the probability of adjustment is exogenously determined, firms might not get the chance to change prices, even when their current prices are suboptimal. Given that firms' adjustments are history independent, this mechanism translates to large adjustments along the intensive margin to make up for the inability to reset prices in the future. In comparison, the difference in the output-destabilizing nature of price flexibility between these two versions boils down to the key pricing mechanism that Golosov and Lucas (2007) have alluded to: under menu costs, firms can also adjust along the extensive margin, so long as the gain is sufficiently high for doing so. Since a demand shock largely shifts the entire distribution of price changes, increases in price flexibility imply a more stable output response under menu costs as more firms can change prices promptly and therefore do not need to compensate for the possibility that they may not do so in the future.[21]

4.4. Welfare Implications

We next examine the welfare implications for output destabilization under high price flexibility by calculating the present discounted value of the utility function ($\mathbb{W}$) while varying the implied price flexibility. To guarantee that our calculation of welfare does not depend on any particular draw of the shock series, we repeat our simulation given the policy function described in Section 3 1000 times and then take the average of $\mathbb{W}$ over these 1000 samples. We next plot this average value of $\mathbb{W}$ over time against the corresponding implied price flexibility $(1-\gamma)$ under our benchmark model in Figure 6.

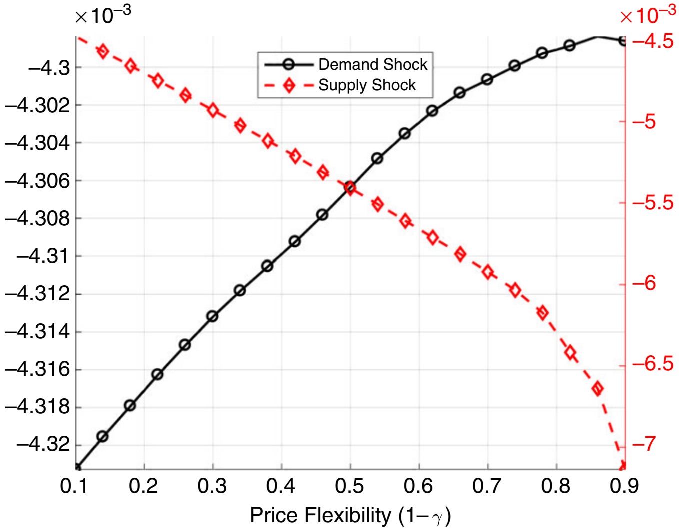
Under supply shocks, increases in price flexibility imply declines in welfare. This result is rather unsurprising, given that price flexibility is largely output-destabilizing under supply shocks. Under demand shocks, on the other hand, since price flexibility is not necessarily output-destabilizing, increases in implied price flexibility are welfare improving as evidenced in Figure 6.

5. EXTENSIONS

In this section, we solve and simulate the model under our baseline specification in Section 4, but with several alterations to a number of key parameters or targeted moments of the model.

5.1. Sensitivity of Monetary Policy Responses

As noted by Bhattarai et al. (2018), the extent to which price flexibility is output-destabilizing depends on the aggressiveness of the central bank's responses to changes in inflation in a standard Calvo setting. A natural question arises regarding the extent to which our result that price flexibility is not output-destabilizing

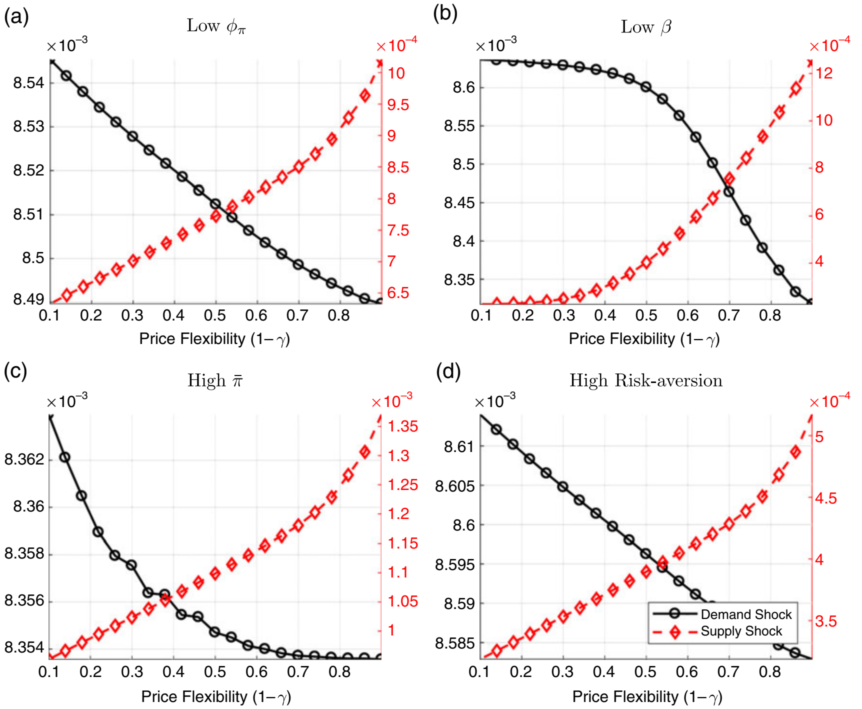


Notes. This figure plots welfare under demand shocks and supply shocks. To generate these series, we simulate the model for 1000 periods and 1000 firms and calculate the corresponding statistics.

FIGURE 6. Welfare and price flexibility under menu costs.

under menu costs is sensitive to our choice of ϕ_π—the central bank's responsiveness to the state of the economy. To explore this possibility, here we repeat the exercise in Section 4 with $\phi_\pi = 1.25$ instead of $\phi_\pi = 1.5$ as in our benchmark calibration in Section 3. A lower value of ϕ_π here implies that the central bank is less responsive to a change in inflation. We plot, in Panel (a) of Figure 7, output volatility against different implied levels of price flexibility. Similar to the benchmark model, here we alter the size of the menu cost χ to vary the implied price flexibility $(1 - \gamma)$.

As evidenced in Panel (a) of Figure 7, output responses to demand shocks become less volatile with decreases in the size of the menu cost. Intuitively, since firms can respond promptly to demand shocks that can make their prices suboptimal under menu costs, as the cost of changing prices becomes smaller, the price distribution becomes more compact, which implies smaller and shorter-lived aggregate inflation responses. Such lackluster inflation responses imply slow nominal interest rate responses from the central bank and, hence, less volatile responses of the real interest rate. Under Calvo models, in comparison, the firms that get to change their prices need to do so preemptively, since they cannot respond immediately to unexpected demand shocks that make their current prices suboptimal. This implies large and persistent responses of inflation, which is reflected in higher real interest rate volatility when the central bank is not aggressive.[22] All in all, we find the result in Section 4 holds when the nominal interest rate does not respond aggressively to inflation that under menu costs, price flexibility is not necessarily output-destabilizing under demand shocks. On



Notes. Unless otherwise noted, we simulate the model for 1000 periods and 1000 firms over 1000 samples using our baseline calibration. Under "Low ϕ_π," we set $\phi_\pi = 1.25$, as opposed to 1.5 in the baseline calibration. Under "Low β," we set the subjective discount factor such that the steady-state interest rate is twice the same number under the baseline calibration. Under "High $\bar{\pi}$," we set $\bar{\pi} = 3\%$. Under "High Risk-aversion," we set σ to 5. Apart from the changes highlighted on top of each subfigure, our parameter choices follow Section 3.

FIGURE 7. Output volatility and price flexibility—extensions.

the other hand, since a supply shock can amplify output responses in either direction regardless of the responsiveness of the central bank, it is not surprising to find price flexibility to be output-destabilizing under such a shock.

5.2. Alternative Parameter Choices

A Higher Steady-state Interest Rate. How output-destabilizing is price flexibility when we move from a period with an expansionary monetary policy to a period with a contractionary policy? To answer this question, we change the subjective discount rate β so that the flexible price steady-state value for the *net* interest rate $R_t - 1$ (annualized) is twice that of the baseline model (i.e., 2.48% instead of 1.24%). We plot, in Panel (b) of Figure 7, output volatility against different levels of implied price flexibility. Similar to our benchmark results in Section 4, we find that price flexibility to be output-destabilizing under supply shocks, but not necessarily so under demand shocks.

A Higher Target Inflation Rate. We next explore the extent to which a higher target inflation rate alters the output-destabilizing nature of price flexibility by increasing $\bar{\pi}$ to 3% from 2% under the baseline specification. Since firms' pricing decisions depend not only on their own draws of idiosyncratic shocks but also on the aggregate state of the economy, the impact of increasing the inflation target might vary from one firm to another. We plot output volatility against price flexibility in Panel (c) of Figure 7 with $\bar{\pi} = 3\%$ and find a higher target inflation rate to have little impact on our baseline results in Section 4.

More Risk-averse Consumers. The extent to which a demand shock alters the inter-temporal condition for the consumer depends on how risk-averse the consumer is. Naturally, it follows that any increase in the degree of relative risk aversion for the consumers can potentially impact the transmission of the real interest rate to output as σ controls the curvature of the utility function. To understand how this channel materializes in the model, we ramp up the degree of relative risk aversion σ for consumers from 3 under the baseline to 5. We plot the corresponding result for this case in Panel (d) of Figure 7. Once again, we find our results in Section 4 to hold for both demand and supply shocks when consumers are more risk-averse.

6. CONCLUSION

In this paper, we examined the implications of price flexibility on output volatility under menu costs. Our main result is that the extent to which price flexibility is output-destabilizing depends largely on the nature of the shocks. In particular, we find that under supply shocks, price flexibility (i.e., lower menu costs) is output-destabilizing. Under demand shocks, we do not find price flexibility to be output-destabilizing. We illustrate these results using a menu cost model calibrated to Japanese micro-price data and note that while our main result, at first glance, is similar to the answer provided by the recent literature that assumes Calvo pricing (see, e.g., Bhattarai et al. (2018)), the mechanisms and the conditions through which price flexibility is output-destabilizing are different under menu costs.

The intuition behind our results critically hinges on the pricing mechanism of menu costs in the sense that firms are allowed to decide the timing of price changes (i.e., the extensive margin) as well as the size of price changes (i.e., the intensive margin). We illustrate that these results under the benchmark menu cost model are robust to the responsiveness of the policy rate, to alternative target inflation rates, to whether the monetary policy is generally contractionary, and to having more risk-averse consumers.

SUPPLEMENTARY MATERIAL

To view supplementary material for this article, please visit http://doi.org/10.1017/S1365100519001020.

NOTES

1. See, for example, Eggertsson (2011) and more recently Bhattarai et al. (2018).

2. Along the spirit of Caplin and Leahy (1991) and Golosov and Lucas (2007), Gagnon (2009) calibrates a menu-cost model using Mexican retail data and finds that the high volatility of retail prices in this dataset poses a challenge to the conventional time-dependent and first-generation state-dependent pricing models because those models perform poorly when prices are highly volatile.

3. Going forward, price flexibility is measured by the implied probability of changing prices across all firms in simulation under menu costs. Equivalently, this value corresponds to $1-\gamma$, in which γ is the probability that a firm is stuck with its current price under the pricing scheme à la Calvo (1983).

4. The nominal interest rate in our model binds relatively infrequently. The average frequency of ZLB events from our simulation under the baseline calibration across all degrees of implied price rigidity (γ) is 7.53%.

5. I am grateful for the support from the Center for International Price Research at Vanderbilt University.

6. See, for example, Nakamura and Steinsson (2010).

7. Since our dataset is at the monthly frequency and since the raw prices reported are averaged over a month from higher-frequency prices for each good and city combination, we abstract from the treatment of temporary sales in calibrating the model.

8. Equivalently under a standard Calvo pricing model, $1-\gamma$ corresponds to the probability that, in any given period, the firm may reset its price, independent of the history of previous adjustments. γ can be thought of as the implied price rigidity under our menu cost model.

9. We use the 3-month inter-bank interest rate for Japan, which yields an average (annualized) interest rate of 1.24% from 1990:M1 to 2015:M3. Data are from the St. Louis' FRED.

10. We use Japanese data from 1990Q1 to 2015Q3 and plot this series in Figure A.2 in the Online Appendix.

11. Since it is possible to have multiple flexible price steady states (see, e.g., Aruoba et al. (2018)), we consider the steady state in which the inflation rate is strictly positive.

12. Here we use discretization as opposed to collocation methods to take advantage of recent development in GPU-computing. The model is solved around 20 times faster than using collocation methods with a reasonable number of nodes.

13. This aggregate law of motion is similar to the one used in Gagnon (2009). The algorithm using this law of motion is stable and requires a relatively small number of iterations to converge.

14. λ^s is chosen to be 0.1. Changing the parameter only affects the speed of convergence, but not any implication of the model. For brevity, we leave the details of this algorithm in the Online Appendix.

15. For brevity, we leave a discussion of the model's fits with micro-price evidence in the Online Appendix.

16. By changing the size of the menu costs χ, we also change the implied price flexibility of the model $1-\gamma$. Since we use the notation $1-\gamma$ to denote the implied price flexibility, γ is equivalent to the parameter that governs the probability that a firm is stuck with its previous price under standard Calvo models.

17. Taking the natural logarithm of the price ratio p/p^*, with p^* being the optimal price, yields $\ln p - \ln p^*$, which represents the distance between the two prices.

18. We focus on one side of the stylized price distribution for illustration purpose.

19. We do not rescale kurtosis so that a Gaussian distribution has a kurtosis value of 3.

20. Our approach of using the shape of the price distribution to understand the extensive margin (i.e., the timing of the price change) is motivated by the literature on the implications of menu costs in

the data (e.g., Gagnon et al. (2012) and Campbell and Eden (2014)). Using US scanner data, Gagnon et al. (2012) find that while the intensive margin is largely observable in the data, the extensive margin is more difficult to observe directly but can be revealed from the data by examining the shape of the price distribution.

21. Another aspect worth noting is that since whether price flexibility is output-destabilizing under demand shocks depends on the responsiveness of the nominal interest rate under Calvo models, it is possible that our result might be sensitive to such responsiveness as well. In Section 5, we address this issue.

22. As noted by Bhattarai et al. (2018), price flexibility is output-destabilizing when the central bank does not respond aggressively to fluctuations in inflation.

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