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Abstract

This paper proposes a sticky inflation model in which inflation persistence is endogenously generated from the optimizing behavior of forward-looking firms. Although firms change prices periodically, their ability to fully adjust them in response to changes in economic conditions is assumed to be constrained due to the presence of managerial and customer costs of price adjustment. In essence, the model assumes that price stickiness arises from a combination of staggered contracts as in Calvo (1983) as well as quadratic adjustment cost as in Rotemberg (1982). We estimate the model using Bayesian techniques. Our findings strongly support both sources of price stickiness in the U.S. data. The model performs well in matching microeconomic evidence on price setting, particularly regarding the size and frequency of price changes. The paper also shows how incomplete price adjustments in a staggered price contracts model limit the contribution of expectations to inflation dynamics: it generates the delayed response of inflation to demand and monetary shocks, and the observed correlation between inflation and economic activity.

Keywords: Inflation Persistence, Phillips Curve, Sticky Prices, Convex Costs, Incomplete Price Adjustment, Infrequent Price Adjustment.

JEL Classification: E31

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1 Introduction

The standard New Keynesian Phillips curve (NKPC) based on the optimizing behavior of price setters in the presence of nominal rigidities is mostly built on the models of staggered contracts of Taylor (1979, 1980) and Calvo (1983), as well as the quadratic adjustment cost model of Rotemberg (1982). This framework is broadly used in the analysis of monetary policy. Price rigidity works as the main transmission mechanism through which monetary policy impacts the economy.

Although the NKPC has some theoretical appeal, there is growing concern on its empirical shortcomings regarding the ability to match some stylized facts on inflation dynamics and the effects of monetary policy. In particular, the standard NKPC models have been criticized due to the failure to generate inflation persistence.[1] Accordingly, although the price level responds sluggishly to shocks, the inflation rate does not. In addition, these models do not yield the result that monetary policy shocks cause a delayed and gradual effect on inflation. Fuhrer and Moore (1995) and Nelson (1998), among others, point out that in order for a model to fully explain the time series properties of aggregate inflation and output gap, it requires not only the price level but also the inflation rate be sticky.

In response to those critiques, this paper proposes a sticky inflation model that is able to endogenously generate inflation persistence as a result of the optimizing behavior of forward-looking firms. In addition, the model implies that monetary policy shocks first impact economic activity, and subsequently inflation but with a long delay, reflecting inflation inertia. The model is also able to capture the observed joint dynamic correlation between inflation and output gap.

We consider that firms face two sources of price rigidities that are related to both the inability to change prices frequently and the cost of sizable adjustments. Calvo's (1983) staggered price setting has been the most frequently used framework in the literature to derive the NKPC, with a fraction of firms completely adjusting their prices to the optimal level at discrete time intervals. Another popular framework is Rotemberg (1982) in which firms set prices to minimize deviations from the optimal price subject to quadratic frictions of price adjustment. While both the Calvo pricing and the quadratic cost of price adjustment are designed to model sticky prices, the former is related to the frequency of price changes while the latter is associated with the size of price changes. In addition, these models have different implication for the frequency of price changes: Rotemberg's model yields continuous price adjustment while Calvo's model implies staggered price setting.

Costs of price adjustment might arise from managerial costs (information gathering and decision making) and customer costs (negotiation, communication, fear of upsetting customers, etc.). For example, Zbaracki, and Ritson, Levy, Dutta, and Bergen (2004), using data from a large U.S. industrial manufacturer, document evidence that those costs of price adjustment are sizable and convex. However, in contrast to the implication of the Rotemberg pricing, the company that faces convex costs of price adjustment does not change prices continuously but only annually because "it is not the culture" of that industry to have frequent price changes. The culture instead implies that prices are fixed by implicit contracts for several periods. This is also found in a survey of around 11,000 firms in the Euro area by

[1] See, for example, Fuhrer and Moore (1995), Nelson (1998), McCallum (1999), Gali and Gertler (1999), Mankiw (2002), Walsh (2003), Sbordone (2007), Rudd and Whelan (2005, 2006, 2007), Angeloni, Aucremanne, Ehrmann, Gali, Levin, and Smets (2006), among several others.

Fabiani et al. (2005), in which implicit and explicit contracts theories were ranked, respectively, first and second among the explanations for price stickiness.

This article proposes a model that combines staggered price setting and quadratic costs of price adjustment in a unified framework. Firms face two decision problems: when to change prices - associated with the Calvo pricing, and how much to change prices - related to quadratic costs of price adjustment. Firms face quadratic adjustment costs only when they decide to change prices, which rather than fixed, varies with the magnitude of the change. The solution of the model implies that, first, prices are not continuously adjusted and, second, firms that are able to change prices do not fully adjust them due to the presence of convex adjustment costs. Inflation persistence is endogenously generated as a consequence of this incomplete and infrequent price adjustment.

Several authors have proposed alternative price settings that can account for some of the empirical facts on inflation and output. The most popular ones are extensions of Calvo's staggered prices based on backward indexation rules, and staggered price contracts resulting from infrequent information updating. These models assume that a fraction of the firms could set their prices optimally each period while the rest adjusts prices according to past aggregate inflation (hybrid NKPC models) or based on outdated information (sticky information models). Although these models are able to generate inflation persistence, either they also imply that firms adjust prices continuously and/or that a fraction of the firms is backward-looking.[2] The empirical implication that prices change frequently in these models contradicts widespread micro-data studies. A recent extensive literature on micro-data shows pervasive evidence of infrequent price adjustments. The finding across countries and different data sources is that firms keep prices unchanged for several months.[3]

Our model differs from the Calvo-cum-indexation models in which inflation inertia arises from firms' backward-looking behavior. In our model, inflation persistence is endogenously generated instead from forward-looking firms with optimizing behavior regarding both the size and frequency of price adjustments. The combination of incomplete and infrequent price adjustment generates inflation persistence without introducing backward-looking firms. Further, in contrast to the indexation models and sticky information models, prices are not continuously adjusted in the proposed model.[4] The new Phillips curve based on dual stickiness nests the standard NKPC as a special case (Calvo pricing) and offers an alternative to the sticky information Phillips curve and the ad-hoc hybrid NKPC with backward-looking firms.

[2]See, e.g., Mankiw and Reis (2002), Christiano, Eichenbaum, and Evans (CEE 2005), and Smets and Wouters (2003, 2007). Notice that continuously price updating is an implication of many other New Keynesian models including Rotemberg (1982) or Kozicki and Tinsley (2002), among several others.

[3]See, e.g. Klenow and Kryvtsov (2008), Alvarez, Dhyne, Hoeberichts, Kwapil, Le Bihan, Lunnemann, Martins, Sabbatini, Stahl, Vermeulen, and Vilmunen (2006), Alvarez (2008), Klenow and Malin (2010), Eichenbaum, Jaimovich, and Rebelo (2011), etc. In addition, Blinder, Canetti, Lebow, and Rudd (1998) and Zbaracki, Ritson, Levy, Dutta, and Bergen (2004) provide micro-evidence for variable costs, including managerial and customer costs. International evidence is shown in Angeloni et al. (2006), Alvarez (2008), Nakamura and Steinsson 2008), Bils, Klenow, and Malin 2012, Klenow and Malin 2010, among several others.

[4] In this respect, our model is appropriately designed for policy analysis since all firms are forward-looking with optimizing behavior, and the implied price dynamics match closely the data, as discussed in detail in Section 4.

Additionally, our sticky price model has different implications on price dispersion from the indexation models. While the indexation models imply that price dispersion varies with a *change* in the inflation rate due to the counterfactual assumption of continuous price adjustments (Giannoni and Woodford 2002), the proposed model implies that price dispersion increases with the magnitude of the inflation rate. In the indexation models a fraction of prices is adjusted optimally, while the remaining prices are updated by automatic indexation to lagged inflation. Accordingly, price dispersion can be inaccurately measured since the prices that may otherwise remain unchanged are instead assumed to be adjusted according to an indexation rule (Chari, Kehoe, and McGrattan 2009). In contrast, our model, as in the standard Calvo price setting, assumes that price dispersion is measured consistently with microeconomic evidence since some prices are optimally adjusted and others remain unchanged.[5]

Our dynamic stochastic general equilibrium (DSGE) model is estimated using Bayesian techniques. Empirical results indicate strong evidence of incomplete and infrequent price adjustment based on the parameter estimates, supporting the proposed model. Thus, the model provides a theoretical foundation on inflation inertia. In addition, the estimates closely match extensive micro-data evidence regarding the size of price adjustment. In particular, we find that the model has the ability to generate small and even large price changes observed from micro-data. The reason is that the introduction of incomplete price adjustment in a staggered price contracts model leads to an amplification of the impact of cost-push shocks on inflation (large price changes) and a reduction of the response of inflation to demand and monetary shocks (small price changes).[6]

Our results also show that our model produces relatively more frequent small price changes than models based on the standard NKPC with Calvo pricing, consistently with microeconomic evidence. Klenow and Kryvtsov (2008) document that the Calvo model fails to generate as many small price changes as observed in the micro-data collected for the Consumer Price Index (CPI). On the other hand, our simulation exercise shows that extensions of the Calvo pricing model such as the hybrid NKPC of Smets and Wouters (2007) and models based on the quadratic adjustment cost of Rotemberg (1982) generate too many small price adjustments due to the assumption of continuous price adjustments.

Another result is that the new sticky inflation model implies a delayed and gradual response of inflation to a monetary policy shock, which is in accord with the persistence in inflation observed in

[5]The intuition behind this implication is as follows. Suppose that there are only two goods, A and B, in the economy. The price of good A rises, while the price of the other is fixed in a given period. In this case, the aggregate inflation rate rises due to good A, and price dispersion measured by the difference of the goods prices will vary with the size of inflation. The larger the price adjustment, the larger the inflation rate and price dispersion (as well as the welfare loss, Woodford 2003). In contrast to the actual price dispersion, the indexation models assumption of continuous price adjustment counterfactually predicts that the price of B changes with the previous level of inflation. Accordingly, price dispersion varies with the difference between inflation and its lagged value, instead of with the level of inflation (see Giannoni and Woodford, 2002, for detailed explanations). Due to this counterfactual assumption, the indexation models can lead to misleading results when it is used for policy analysis (Chari, Kehoe, and McGrattan 2009), as they inaccurately describe the path of actual price and, therefore, price dispersion.

[6] Our model differs from the standard NKPC with Calvo pricing in that the latter implies that firms make relatively large price adjustments in response to demand and monetary shocks and small price adjustments in response to cost shocks. On the other hand, the hybrid NKPC models are similar to ours with regard to the muteness of the impact of monetary shock on inflation, which is caused by inflation persistence. Despite this similarity, the hybrid NKPC does not produce large price changes due to continuous price adjustment, while our model does a plausible job in producing large price changes due to infrequent price adjustment.

the data. The baseline NKPC with Calvo pricing fails to generate a hump-shaped response of inflation to a monetary policy shock, as inflation falls instantly in response to this shock, displaying no inertia (Christiano, Eichenbaum, and Evans 2005). By contrast, in the proposed model the policy shock raises interest rate and, thus, has a negative impact on output gap and inflation, generating a delayed response of inflation due to the incomplete and infrequent price adjustments.

Regarding the relationship between inflation and output gap, the standard NKPC with Calvo pricing fails to generate the observed low contemporaneous correlation between current output gap and inflation. Our simulation exercise shows that the assumption that firms are able to adjust prices completely in response to changes in economic conditions leads to an unrealistically high correlation between the two variables. The introduction of incomplete price adjustment into a staggered price contracts setting works to reduce the impact of demand-side shocks on prices, leading to a reduction in the estimated positive correlation between inflation and output gap.

The remainder of this paper is organized as follows. Section 2 derives the new sticky inflation model. Section 3 introduces the associated small-scale dynamic stochastic general equilibrium model. Section 4 reports empirical and simulation results, and Section 5 concludes.

2 Firms' Problems and the Phillips Curve

We assume that the economy has two types of firms: a representative final goods-producing firm and a continuum of intermediate goods-producing firms.

2.1 The Final Goods-Producing Firm

The final goods-producing firm purchases a continuum of intermediate goods, Y_{it}, at input prices, P_{it}, indexed by $i \in [0,1]$. The final good, Y_t, is produced by bundling the intermediate goods as follows

$$Y_t = \left[\int_0^1 Y_{i,t}^{1/\lambda_f} di\right]^{\lambda_f} \tag{1}$$

where $1 \leq \lambda_f < \infty$. The final goods-producing firm chooses $Y_{i,t}$ to maximize its profit in a perfectly competitive market taking both input, $P_{i,t}$, and output prices, P_t, as given. The objective of the final goods-producing firm is expressed as

$$P_t Y_t - \int_0^1 P_{i,t} Y_{i,t} di \tag{2}$$

subject to the technology described in (1). The first order condition of the final-goods-producing firm implies that

$$Y_{i,t} = \left(\frac{P_{i,t}}{P_t}\right)^{-a} Y_t \tag{3}$$

where $a \equiv \lambda_f/(\lambda_f - 1)$ measures the constant price elasticity of demand for each intermediate good. The relationship between the prices of the final and intermediate goods can be obtained by integrating (3),

$$P_t = \left[\int_0^1 P_{i,t}^{1/(1-\lambda_f)} di\right]^{1-\lambda_f}. \tag{4}$$

Equation (4) is derived from the fact that the final goods-producing firm earns zero profits. The final good price can be interpreted as the aggregate price index.

2.2 The Intermediate Goods-Producing Firm

As seen in the literature, the NKPC is most commonly derived using Calvo's (1983) staggered price setting in which a fraction $(1-\theta)$ of firms reset prices to optimize profit while the remaining firms maintain their prices unchanged in any given period. In the Calvo economy, as implied by equation (4), the aggregate price level evolves according to

$$P_t^{\frac{1}{1-\lambda_f}} = (1-\theta)\tilde{P}_t^{\frac{1}{1-\lambda_f}} + \theta P_{t-1}^{\frac{1}{1-\lambda_f}} \tag{5}$$

where $\tilde{P}_t$ denotes the aggregate optimal price set by the intermediate good-producing firms. The average duration of price contracts is calculated as $1/(1-\theta)$ in the Calvo economy. Since individual prices are optimized in a staggered manner, the aggregate price level evolves sluggishly, making the aggregate price depend on its own lag.

Another popular way of introducing nominal rigidities is to assume that firms face variable costs when changing their prices. Rotemberg (1982) proposes that firms face quadratic costs of price adjustment. Several dimensions of managerial and customer relations may imply that the costs of price adjustment is proportional to its size. Since these costs increase with the magnitude of price adjustment, firm's ability to fully adjust prices could be constrained, making the aggregate price sticky with respect to the size of price changes. We assume that each intermediate goods-producing firm faces the quadratic price adjustment cost given by

$$QAC = \frac{c}{2}\left(\frac{\tilde{P}_{i,t}}{\tilde{P}_{i,t-j}} - 1\right)^2 Y_t \tag{6}$$

where $\tilde{P}_{i,t}$ and $\tilde{P}_{i,t-j}$ denote firm i's optimal prices in period t and $t-j$, respectively. When the firm i has no price adjustments between these two periods, the price adjustment cost in period t is determined by the difference between $\tilde{P}_{i,,t}$ and $\tilde{P}_{i,t-j}$. Equation (6) implies that it is costly for current individual price to deviate from past price level, which makes price sticky. The cost of adjusting prices is zero when there is no change in nominal price. Our setup is slightly different from that of Rotemberg (1982) since we assume that firms cannot adjust prices continuously.

Zbaracki et al. (2004) document quantitative and qualitative evidence that managerial and customer costs of price adjustment are convex using data from a large U.S. industrial manufacturer, as quoted below:

"The managerial costs of price adjustment increase with the size of the adjustment because the decision and internal communication costs are higher for larger price changes. The larger the proposed price change, the more people are involved, the more supporting work is done, and the more time and attention is devoted to the price change decisions. ... Customer costs of price adjustment also increase with the size of the adjustment because larger price changes lead to both higher negotiation costs and higher communication costs. ... Given the convexity of the price adjustment costs, pricing managers often felt it was not worth the fight to make major changes, and would propose smaller ones." (Zbaracki et al. 2004 p. 524)

Their findings indicate that the managerial costs and the customer costs are, respectively, 6 and 20 times greater than the menu costs. Although the company investigated by Zbaracki et al. (2004) faces convex costs of price adjustment, it does not change prices continuously as implied by Rotemberg's sticky price model:

"We can't change prices biannually, it is not the culture here."- Pricing manager" (Zbaracki et al. 2004 p. 525)

The company's infrequent price adjustment can be explained by implicit contract theory. Fabiani et al. (2005) surveyed around 11,000 firms in the Euro area and found that implicit and explicit contracts theories ranked first and second among the explanations of price stickiness. In sum, the company investigated by Zbaracki et al. (2004) adjusts its prices annually, but incompletely due to convex costs of price adjustment.

Both the Calvo pricing and the quadratic cost of price adjustment are similar modeling devices in the sense that they lead to sticky prices. However, they yield different implications with respect to the frequency and size of price adjustment. While the Calvo model is associated with the frequency of price changes, the quadratic price adjustment cost is related to the magnitude of price changes. These pricing models are closely associated with the decision problems faced by firms, regarding when and by how much to change prices. The Calvo pricing is designed to capture infrequent price adjustments that arise from implicit and explicit contracts, coordination failure, and fixed costs of changing prices.[7] On the other hand, the Rotemberg pricing is closely related to variable costs such as managerial costs (information gathering and decision making costs), customer costs (negotiation and communication costs), and manager's "fear of antagonizing customers" (Rotemberg 1982, 2005, Zbaracki et al. 2004). It is worth emphasizing that in our framework firms face variable costs of price adjustment only when they decide to change prices. Evidence on these frictions are extensively found in the the literature as in Zbaracki et al. (2004), and in the surveys by Blinder et al. (1998) or Fabiani et al. (2005).

The intermediate goods-producing firm maximizes real profit from selling its output in a monopolistically competitive goods market, assuming that its price is fixed with the Calvo probability θ in any given period. Additionally, the firm faces the quadratic cost of adjusting its price. The firm i chooses $\tilde{P}_{i,t}$ to maximize

$$E_t \sum_{k=0}^{\infty} (\theta\beta)^k \left[\frac{\left(\tilde{P}_{i,t} - exp\left(e_{\pi,t}\right) mc_{t+k} P_{t+k}\right) Y_{i,t+k}}{P_{t+k}} \right] - \frac{c}{2} \left(\frac{\tilde{P}_{i,t}}{\tilde{P}_{i,t-j}} - 1 \right)^2 Y_t \tag{7}$$

[7] Blinder et al. (1998) document evidence that the theory of coordination failure ranked first in the United States as the main reason for infrequent price changes. As Nakamura and Steinsson (2013) point out, coordination failure in price setting has two essential elements. First, pricing decisions are staggered since firms wait for other firms to change their prices. Second, firms that have an opportunity to adjust prices will adjust them partially in response to various shocks because other firms keep their prices unchanged. In this respect, our model shares these essential elements of the theory of coordination failure even though pricing does not depend on the behavior of other firms. The fundamental difference between these two theories emerges from the ability to generate a lagged inflation term in the Phillips curve. We later show that our model is able to generate small and large price changes while, as Klenow and Willis (2006) point out, a model with strategic complementarities based on Kimball (1995) is hard to reconcile with large price changes.

subject to the demand function described by equation (3). mc_t represents real marginal cost, and $e_{\pi,t}$ is the cost-push shock. Firm i's profit depends on $\tilde{P}_{i,t}$ when it cannot re-optimize its price in period $t+k$, with integer $k \in [0, \ \infty]$. The firm does not face the quadratic adjustment cost in the future as long as the price chosen in period t is not reset. The firm plans to keep the optimal price unchanged with the probability θ in the future. In this respect, this setup differs from that of Rotemberg (1982) that assumes continuous price adjustment. In addition, the firms who reset their prices in period t are heterogeneous with respect to the time elapsed since their last price adjustments. When the firm i adjusts its price in period $t-j$ and t, where integer $j \in [1, \infty]$, and keeps the price unchanged between these two periods, the price adjustment cost depends on the distance between $\tilde{P}_{i,t-j}$ and $\tilde{P}_{i,,t}$. Since the firms resetting prices in period t differ with respect to the time elapsed since their last price adjustment, the aggregate optimal price of the firms resetting prices in period t, $\tilde{P}_t$, can be written as a weighted average of their optimal prices, which is given by

$$\tilde{P}_t^{\frac{1}{1-\lambda_f}} = (1-\theta)\,\tilde{P}_{l_1,t}^{\frac{1}{1-\lambda_f}} + (1-\theta)\,\theta\tilde{P}_{l_2,t}^{\frac{1}{1-\lambda_f}} + (1-\theta)\,\theta^2\tilde{P}_{l_3,t}^{\frac{1}{1-\lambda_f}} + \cdots = \sum_{j=1}^{\infty}(1-\theta)\,\theta^{j-1}\tilde{P}_{l_j,t}^{\frac{1}{1-\lambda_f}} \tag{8}$$

where $\tilde{P}_{l_j,t}^{\frac{1}{1-\lambda_f}} \equiv \int_{i\in l_{j,}} \tilde{P}_{i,t}^{\frac{1}{1-\lambda_f}} di$.[8] The set l_j includes the firms that adjust prices in period $t-j$ and t and that keep their prices unchanged between these two periods. The Calvo pricing implies that, *among the cohort of the firms who reset their prices in period* t, only a fraction $(1-\theta)\,\theta^{j-1}$of firms adjusts their prices in period $t-j$ and keep their prices unchanged until period $t-1$. When $j=2$, the probability that a firm adjusts its price in period $t-2$ and keep it unchanged until period $t-1$ is computed to be $(1-\theta)\,\theta$ in the Calvo economy.[9]

Plugging (3) into (7) and then rearranging it in terms of the relative price, $\tilde{p}_{i,t} \equiv \tilde{P}_{i,t}/P_t$, yields

$$E_t\sum_{k=0}^{\infty}(\theta\beta)^k\left[\left(\tilde{p}_{i,t}\tilde{X}_{t,k} - exp\,(e_{\pi,t})\,mc_{t+k}\right)(\tilde{p}_{i,t}\tilde{X}_{t,k})^{-a}Y_{t+k}\right] - \frac{c}{2}\left(\frac{\tilde{p}_{i,t}}{\tilde{p}_{i,t-j}}\pi_t\pi_{t-1}\cdots\pi_{t-j+1} - 1\right)^2 Y_t \tag{9}$$

where $\tilde{X}_{t,k} \equiv 1/\pi_{t+1}\pi_{t+2}...\pi_{t+k}$ when $k>0$, and $\tilde{X}_{t,k} \equiv 1$ when $k=0$.[10] The first order condition of (9) with respect to $\tilde{p}_{i,t}$ is given by

$$E_t\sum_{k=0}^{\infty}(\theta\beta)^k\left[\tilde{X}_{t,k}^{-a}\tilde{p}_{i,t}^{-a-1}Y_{t+k}\left((1-a)\tilde{p}_{i,t}\tilde{X}_{t,k} + (a)exp(e_{\pi,t})mc_{t+k}\right)\right]$$

$$= c\left(\frac{\tilde{p}_{i,t}}{\tilde{p}_{i,t-j}}\pi_t\pi_{t-1}\cdots\pi_{t-j+1} - 1\right)\frac{1}{\tilde{p}_{i,t-j}}\pi_t\pi_{t-1}\cdots\pi_{t-j+1}Y_t. \tag{10}$$

[8] The relationship between the aggregate price level and the aggregate optimal price is described by $P_t^{\frac{1}{1-\lambda_f}} = (1-\theta)\tilde{P}_t^{\frac{1}{1-\lambda_f}} + \theta P_{t-1}^{\frac{1}{1-\lambda_f}}$.

[9] When the quadratic cost of price adjustment is assumed to be zero, the model collapses into the standard NKPC in which firms completely adjust their prices, regardless of the history of their price adjustment.

[10] Notice that the quadratic adjustment cost can be written as $\frac{c}{2}\left(\frac{\tilde{p}_{i,t}}{\tilde{p}_{i,t-j}} - 1\right)^2 Y_t$ when the cost of adjusting prices is defined as $\left(\frac{\tilde{P}_{i,t}/P_t}{\tilde{P}_{i,t-j}/P_{t-j}} - 1\right)^2 Y_t$ instead of $\left(\frac{\tilde{P}_{i,t}}{\tilde{P}_{i,t-j}} - 1\right)^2 Y_t$. The terms related to current and lagged inflation can be eliminated from the model with the alternative real adjustment cost. We study the role of the inflation terms in generating inflation persistence in Section 4.4 and find that inertia in inflation can be produced with the alternative specification of the price adjustment cost.

Log-linearizing the first order condition yields

$$E_t \sum_{k=0}^{\infty} (\theta\beta)^k \left[\hat{\pi}_{t+k} + (1-\theta\beta)\left(e_{\pi,t+k} + \hat{mc}_{t+k}\right)\right] = \hat{\tilde{p}}_{i,t} + \hat{\pi}_t + \frac{c(1-\theta\beta)}{a-1}\left(\hat{\tilde{p}}_{i,t} - \hat{\tilde{p}}_{i,t-j} + \hat{\pi}_t + \hat{\pi}_{t-1} + \cdots + \hat{\pi}_{t-j+1}\right) \tag{11}$$

where $\hat{\tilde{p}}_{i,t}$, $\hat{X}_{t,k}$, and $\hat{mc}_{t+k}$ are the log-deviation (denoted by hat) of $\tilde{p}_{i,t}$, $\tilde{X}_{t,k}$, and mc_{t+k} from their steady state values, respectively. Arranging (11) gives rise to

$$\left(1 + \frac{c(1-\theta\beta)}{a-1}\right)\hat{\tilde{p}}_{i,t} + \hat{\pi}_t + \frac{c(1-\theta\beta)}{a-1}\left(\hat{\pi}_t + \hat{\pi}_{t-1} \cdots + \hat{\pi}_{t-j+1}\right) =$$

$$\frac{c(1-\theta\beta)}{a-1}\hat{\tilde{p}}_{i,t-j} + E_t \sum_{k=0}^{\infty} (\theta\beta)^k \left[\hat{\pi}_{t+k} + (1-\theta\beta)\left(e_{\pi,t+k} + \hat{mc}_{t+k}\right)\right]. \tag{12}$$

When $c = 0$ as in the standard Calvo model, current real price $\hat{\tilde{p}}_{i,t}$ is determined by current and expected values of future inflation and real marginal cost. In contrast to the implication of Calvo model, our model implies that current price is affected by lagged price. Integrating both sides of (11) with respect to $i \in l_j$ yields

$$E_t \sum_{k=0}^{\infty} (\theta\beta)^k \left[\hat{\pi}_{t+k} + (1-\theta\beta)\left(e_{\pi,t+k} + \hat{mc}_{t+k}\right)\right] = \hat{\tilde{p}}_{l_j,t} + \hat{\pi}_t + \frac{c(1-\theta\beta)}{a-1}\left(\hat{\tilde{p}}_{l_j,t} - \hat{\tilde{p}}_{l_j,t-j} + \hat{\pi}_t + \hat{\pi}_{t-1} \cdots + \hat{\pi}_{t-j+1}\right) \tag{13}$$

where $\hat{\tilde{p}}_{l_j,t} \equiv \int_{i\in l_j,} \hat{\tilde{p}}_{i,t} di$.[11] Rearranging (13) delivers the aggregate optimal price of the firms ($i \in l_j$), which is given by

$$\hat{\tilde{p}}_{l_j,t} = \theta\beta E_t \left(\hat{\tilde{p}}_{l_j,t+1} + \left[\frac{a-1}{a-1+c(1-\theta\beta)}\right]\hat{\pi}_{t+1}\right) + \frac{(1-\theta\beta)(a-1)}{a-1+c(1-\theta\beta)}\left(\hat{mc}_t\right)$$

$$+\frac{c(1-\theta\beta)}{a-1+c(1-\theta\beta)}\left(\hat{\tilde{p}}_{l_j,t-j} - \theta\beta\hat{\tilde{p}}_{l_j,t-j+1} + \sum_{h=0}^{j-1} E_t\left[\theta\beta\hat{\pi}_{t-h+1} - \hat{\pi}_{t-h}\right]\right) + \varepsilon_{\pi,t}. \tag{14}$$

The disturbance, $\varepsilon_{\pi,t} \equiv \frac{(1-\theta\beta)(a-1)}{a-1+c(1-\theta\beta)} e_{\pi,t}$, to the optimal price is the reparameterized cost-push shock, which follows an AR(1) process, $\varepsilon_{\pi,t} = \delta_\pi \varepsilon_{\pi,t-1} + \nu_{\pi,t}$ with $\nu_{\pi,t} \sim N(0, \sigma_\pi^2)$. Equation (14) shows that while the contribution of inflation expectations to the optimal price, $\hat{\tilde{p}}_{l_j,t}$, increases with the Calvo pricing parameter θ due to $\frac{\partial}{\partial\theta}\left(\frac{\theta\beta(a-1)}{a-1+c(1-\theta\beta)}\right) > 0$, it declines with the quadratic price adjustment cost c due to $\frac{\partial}{\partial c}\left(\frac{\theta\beta(a-1)}{a-1+c(1-\theta\beta)}\right) < 0$. The coefficient on the lagged price $\hat{\tilde{p}}_{l_j,t-j}$ increases as the adjustment cost parameter c rises due to $\frac{\partial}{\partial c}\left(\frac{c(1-\theta\beta)}{a-1+c(1-\theta\beta)}\right) > 0$, while it declines as the duration of nominal price contracts rises due to $\frac{\partial}{\partial\theta}\left(\frac{c(1-\theta\beta)}{a-1+c(1-\theta\beta)}\right) < 0$. The dependence of the optimal price on its own lagged value in our model prevents it from being adjusted drastically, yielding an inertia in inflation dynamics. Since inflation arises due to the firms that reset their prices to optimal levels, the sluggish adjustment of

[11] The most recent three price adjustments of each firm in the cohort l_j occur at time t, $t-j$, and at a particular time period $t-j-k$ where integer $k \in [1, 2, \cdots, \infty]$. Notice that k differs across the firms in the cohort l_j while j is the same in the cohort l_j . The aggregated optimal price in the cohort l_j at time $t-j$ can be written as $\hat{\tilde{p}}_{l_j,t-j} = \hat{\tilde{p}}_{t-j}$ where $\hat{\tilde{p}}_{t-j}$ is the aggregate optimal price for all the firms that adust prices at time $t-j$. This equality holds because the firms in the cohort l_j are randomly chosen among all the firms that adust prices at time $t-j$.

the optimal price yields inflation persistence. Turning to the coefficient of real marginal cost, we find that both infrequent and incomplete price adjustments reduce the response of the optimal price to real marginal cost due to $\frac{\partial}{\partial c}\left(\frac{(1-\theta\beta)(a-1)}{a-1+c(1-\theta\beta)}\right) < 0$ and $\frac{\partial}{\partial \theta}\left(\frac{(1-\theta\beta)(a-1)}{a-1+c(1-\theta\beta)}\right) < 0$. In this respect, our model shares some properties of the Calvo model combined with strategic complementarity in which, along with price stickiness, the presence of strategic complementarity in price setting diminishes the response of "reset prices" to real marginal cost.[12] However, our model differs from sticky price models with strategic complementarity, as in the latter the optimal price does not rely on its own lagged value. In our model, the dependence of inflation on its own lag generates a hump shaped response of inflation to a monetary shock. In section 4, we show that our model does a good job in matching the empirical response of inflation to a monetary shock. We also study whether abstracting the term, $\sum_{h=0}^{j-1} E_t\left[\theta\beta\hat{\pi}_{t-h+1} - \hat{\pi}_{t-h}\right]$ from (14) affects the performance of the model with respect to the ability to generate a sluggish response of inflation to a monetary shock.

Log-linearizing (5) and (8) associated with the Calvo pricing delivers the following equations:

$$\hat{\tilde{p}}_t = \frac{\theta}{1-\theta}\hat{\pi}_t \tag{15}$$

$$\hat{\tilde{p}}_t = (1-\theta)\sum_{j=1}^{\infty}\theta^{j-1}\hat{\tilde{p}}_{l_j,t}. \tag{16}$$

Equation (15) and (16) show that inflation arises due to the firms resetting their prices. In our setup, there is no closed-form solution for the Phillips curve since firms resetting prices differ in terms of the time elapsed after last price adjustment. Inflation dynamics are described by (14), (15), and (16).

The proposed model nests the standard NKPC model with Calvo setting as a particular case. When the quadratic cost of price adjustment is zero, our model collapses into the standard NKPC of the form

$$\hat{\pi}_t = \beta E_t\hat{\pi}_{t+1} + \frac{(1-\theta)(1-\theta\beta)}{\theta}\hat{mc}_t + \epsilon_{\pi,t}. \tag{17}$$

Abstracting the quadratic adjustment from the model makes firms choose the same price regardless of when they reset them. As a consequence, the absence of the adjustment cost yields the standard NKPC.

3 A Small Scale DSGE Model

We consider a small scale DSGE model consisting of the IS curve, the Phillips curve, and the Taylor rule, which is standard in the macroeconomics literature except for our proposed firms' pricing behavior. As in Erceg, Levin, and Henderson (2000), Christiano, Eichenbaum, and Evans (2005), and Smets and Wouters (2007), we assume that each household is a monopolistic supplier of a differentiated labor service. It is assumed that perfect consumption insurance is available to each household and full risk

[12] Bils, Klenow and Malin (2012) document evidence against strategic complementarity in that reset prices adjust more rapidly than what New Keynesian models with strategic complementarity predict. However, this issue is controversial. Gopinath, Itskhoki, and Rigobon (2010) study the behavior of U.S. import and export prices, and find that firms raise prices by 0.25% in response to an 1.0% increase in the cumulative exchange rate, since they have adjusted prices last time. They also find that firms adjust imported prices in response to changes in the exchange rate before the previous price adjustments. The findings are consistent with Fitzgerald and Haller (2012) and Burstein and Jaimovich (2012).

sharing allows each household to enjoy the same level of consumption.[13]

The intertemporal utility function of the household is given by $E_t \sum_{k=0}^{\infty} \beta^k \left(\frac{(C_{t+k} - hC_{t+k-1})^{1-1/\sigma}}{1-1/\sigma} - \frac{N_{i,t+k}^{1+\varphi}}{1+\varphi} \right)$, subject to the budget constraint, $C_{t+k} + \frac{B_{t+k}}{P_{t+k}} = \frac{W_{i,t+k}N_{i,t+k}}{P_{t+k}} + exp(-\xi_{t+k-1})(1 + i_{t+k-1})(\frac{B_{t+k-1}}{P_{t+k}}) + \Pi_{t+k}$, where C_t is the composite consumption good, $W_{i,t}$ is the nominal wage for each labor type, Π_t is real profits received from firms, and B_t is the nominal holdings of one-period bonds that pay a nominal interest rate i_t. The parameter h captures the degree of habit in consumption. As in Smets and Wouters (2007), we introduce a risk premium,$-\xi_{t-1}$, into the DSGE model. The model economy results in the IS curve, which is given by

$$y_t = \Gamma_1 y_{t-1} + \Gamma_2 E_t y_{t+1} - \Gamma_3 E_t y_{t+2} - \Sigma \left(i_t - E_t \pi_{t+1} \right) + \varepsilon_{y,t} \tag{18}$$

where $\Gamma_1 \equiv \frac{h}{1+h+h^2\beta}$, $\Gamma_2 \equiv \frac{1+h\beta+h^2\beta}{1+h+h^2\beta}$, $\Gamma_3 \equiv \frac{h\beta}{1+h+h^2\beta}$, and $\Sigma \equiv \frac{\sigma(1-h)(1-h\beta)}{1+h+h^2\beta}$. The term y_t and i_t denote output gap and the nominal interest rate, respectively[14]. We interpret the disturbance term as a preference shock, $\varepsilon_{y,t} \equiv \frac{\sigma(1-h)(1-h\beta)}{1+h+h^2\beta}\xi_t$, which is assumed to follow an AR(1) process, $\varepsilon_{y,t} = \delta_y \varepsilon_{y,t-1} + \nu_{y,t}$ with $\nu_{y,t} \sim N(0, \sigma_y^2)$.

Following Erceg, Levin, and Henderson (2000), we assume that a fraction θ_w of households optimally adjusts their wages and the remaining households keep their wages unchanged in any given period. Then, the wage inflation Phillips curve can be written as

$$\pi_t^w = \beta E_t \pi_{t+1}^w + \kappa_w \left(mrs_t - w_t \right) \tag{19}$$

where $\kappa_w \equiv \frac{(1-\theta_w)(1-\beta\theta_w)}{\theta_w(1+b\varphi)}$. The parameter b is the elasticity of substitution across differentiated labor services, π_t^w is wage inflation, w_t is the real wage rate, and mrs_t is the marginal rate of substitution between consumption and labor, which has the form of $mrs_t = \left(\varphi + \frac{1+h^2\beta}{\sigma(1-h\beta)(1-h)} \right) y_t - \frac{h}{\sigma(1-h\beta)(1-h)} y_{t-1} - \frac{h\beta}{\sigma(1-h\beta)(1-h)} E_t y_{t+1}$. Wage inflation evolves according to (19) while inflation dynamics are governed by (14), (15), and (16), as described previously. The real marginal cost is defined as $mc_t = w_t + n_t - y_t$. We introduce the identity equation that links real wage growth, wage inflation, and price inflation as follows

$$w_t - w_{t-1} = \pi_t^w - \pi_t. \tag{20}$$

since we hold $\frac{W_t/P_t}{W_{t-1}/P_{t-1}} = \frac{W_t}{W_{t-1}} \frac{P_{t-1}}{P_t}$.

The monetary authority adjusts the interest rate in response to expected inflation and output gap through

$$i_t = \rho i_{t-1} + (1 - \rho)(\alpha_\pi E_t \pi_{t+1} + \alpha_y y_t) + \varepsilon_{i,t} \tag{21}$$

where the monetary shock $\varepsilon_{i,t}$ follows an AR(1) process, $\varepsilon_{i,t} = \delta_i \varepsilon_{i,t-1} + \nu_{i,t}$ with with $N(0, \sigma_i^2)$, and ρ measures the degree of interest rate smoothing in monetary policy. We assume that policy makers are forward-looking in stabilizing inflation. However, they adjust the interest rate in response to current

[13] Households are homogeneous with respect to consumption and bond holdings, whereas they are heterogeneous with respect to hours worked and the wage rate they receive from firms.

[14] In this section, the variables with lower-case letters denote log-deviations from their steady state values. We present them without hat for convenience.

economic activity. The monetary authority's responses to inflation and output gap are determined by the parameters α_π and α_y, respectively.

4 Empirical Results

4.1 Data and Priors

The small scale DSGE model has three observed time series – interest rate, output gap, and inflation; and three shocks – demand, monetary, and cost shocks. In order to estimate the DSGE model, we use real GDP, the effective Federal Funds rate, and the GDP deflator from the FRED database of the Federal Reserve Bank of Saint Louis. Real GDP is detrended using Hodrick–Prescott (HP) two-sided filter. We first focus the analysis on the post-1980 period due the concern that the earlier high inflationary period could be a source of inflation persistence. We also estimate the model for the pre-1980 period and for a larger sample that include the Great Inflation and Great Moderation periods, from 1960 to 2008 (subsection 4.8). Additionally, since interest rate was close to zero between 2009 and 2015, our sample ends in 2008:4 to avoid issues related to the zero lower bound and the unusual dynamics during the recent financial crisis.[15]

The priors on the model parameters are summarized in Table 1. We set the parameter a that measures the constant price elasticity of demand for each intermediate good to 6, as commonly done in the related literature. This implies a steady state markup of price over marginal cost of twenty percent (see, e.g., Rotemberg and Woodford 1992, and Ireland 2001). The elasticity of substitution across differentiated labor services, b, is set to 6 suggesting that the wage markup at steady state is twenty percent. We also set the discount factor β to 0.99, as commonly assumed in the literature. The parameter φ is set to be 1.5 as in Gourio and Noualz (2006) who estimates this parameter using monthly panel data from the National Longitudinal Survey of Youth (NLSY). The model is estimated using Bayesian techniques. We use 400,000 draws to estimate the DSGE model, but only start calculating posterior features after 30,000 draws. The Metropolis-Hastings algorithm is applied to obtain the maximum likelihood estimates.

Equation (16) shows that the contribution of $\hat{\tilde{p}}_{l_j,t}$ to the aggregate optimal price $\hat{\tilde{p}}_t$ converges to zero as the time elapsed after last price adjustment increases ($j \to \infty$). Therefore, we restrict the max of integer j to 8 when estimating the model. The probability that firms reset prices in period $t-j$ and t, and keep their prices unchanged between these two periods is $(1-\theta) \times (1-\theta)\,\theta^{j-1}$. When $j = 8$ and the parameter θ is around 0.75, the probability of resetting prices is very close to zero. Extending j to 12 or larger does not change our estimation results, while larger j involves considerable computing time

[15] In subsection 4.8, we compare the results with output detrended using potential output from the Congressional Budget Office (CBO), and detrended using Christiano-Fitzgerald's (CF 2003) one sided-filter. We also estimate and compare the model with inflation in level and detrended inflation. In subsection 4.4 we consider that firms face real adjustment cost rather than nominal adjustment, and that consumers do not display habit formation, for comparison. As shown in these subsection, the evidence on incomplete price adjustment is consistently found regardless of the sample period, choice of variables, real vs nominal adjustment cost, or habit formation.

cost.[16]

4.2 Estimation Results

Table 1 reports estimation results of the proposed sticky inflation DSGE model. The posterior mean estimates of monetary policy parameters ρ, α_π, and α_y are similar to the ones found in the literature. The parameter measuring the degree of interest rate smoothing is estimated to be 0.76. The estimate of α_π associated with the Fed's response to inflation expectations is 1.33, whereas the estimated parameter related to the response of the Fed to output gap is 0.55. The posterior mean of θ, the Calvo measure of degree of nominal rigidity, is estimated to be 0.88 during the Great Moderation period. [17] Additionally, the estimated parameter c associated with variable price adjustment costs is 83.3 and significantly different from zero, even though the Calvo parameter is estimated to be substantially different from zero. This supports evidence that adjustment cost plays an important role in price setting. Figure 1 shows the prior and posterior distributions of θ and c. The 95% confidence intervals of the parameter θ and c are substantially away from zero. Thus, the null hypothesis of no price rigidities with respect to the frequency and size of price adjustment is rejected, supporting the proposed sticky inflation model. The parameter θ_w for staggered wage contracts is estimated to be 0.55, while the estimated parameter σ determining the sensitivity of output gap to real interest rate is 0.09. The estimated standard deviation of the cost-push shock,σ_π, is substantially greater than the standard deviations of the demand shock,σ_y, and monetary shock,σ_i. However, the cost-push shock affects only a small fraction of firms so its impact on inflation is much smaller than on the optimal price.[18]

Table 1: Estimation Results - Proposed DSGE Model

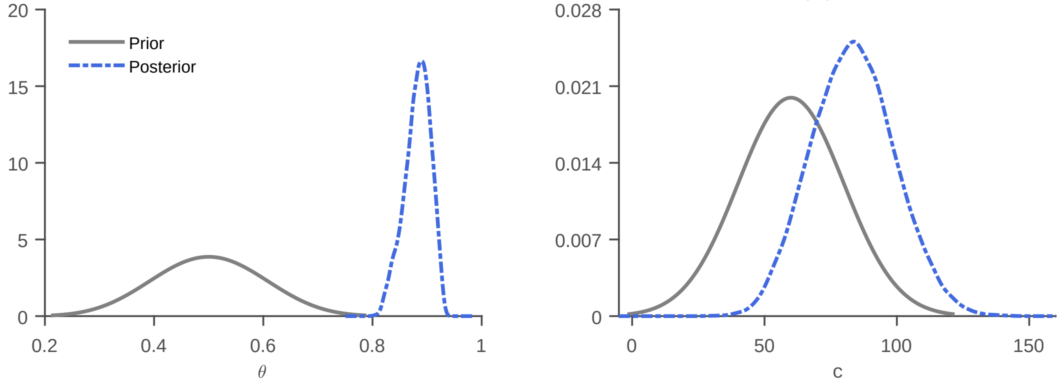
Parameter	Prior Distribution	Prior Mean	Prior St. Dev.	Posterior Mean	95% Confidence Interval
θ	Beta	0.5	0.10	0.88	[0.78, 0.92]
c	Normal	60.0	20.0	83.3	[50.0, 113.3]
θ_w	Beta	0.5	0.10	0.55	[0.38, 0.72]
σ	InvG	0.1	∞	0.09	[0.03, 0.19]
ρ	Beta	0.7	0.05	0.76	[0.69, 0.84]
α_π	Normal	1.5	0.25	1.33	[0.89, 1.78]
α_y	Normal	0.5	0.10	0.55	[0.36, 0.74]
δ_π	Beta	0.5	0.2	0.50	[0.31, 0.76]
δ_y	Beta	0.5	0.2	0.52	[0.33, 0.69]
δ_i	Beta	0.5	0.2	0.74	[0.60, 0.85]
σ_π	Invg	0.1	2.0	6.32	[1.37, 9.38]
σ_y	Invg	0.1	2.0	0.07	[0.04, 0.10]
σ_i	Invg	0.1	2.0	0.46	[0.39, 0.51]

[16] Setting j below or above 12 does not alter our empirical results.

[17] As shown in subsection 4.8, the posterior mean of the Calvo parameter changes substantially across samples. For example, our estimates for samples that include high inflation periods are between 0.55 and 0.59, which is consistent with the fact that firms tend to adjust prices more frequently (lower θ) during high inflationary periods.

[18] As an illustration, suppose that the aggregate optimal price rises by 4 percent due to the cost-push shock. In this case, inflation rises by less than 1 percent since the majority of firms keeps their prices unchanged.

Figure 1: Priors and Posteriors of the Parameters of Calvo Pricing (θ) and Adjustment Cost (c)



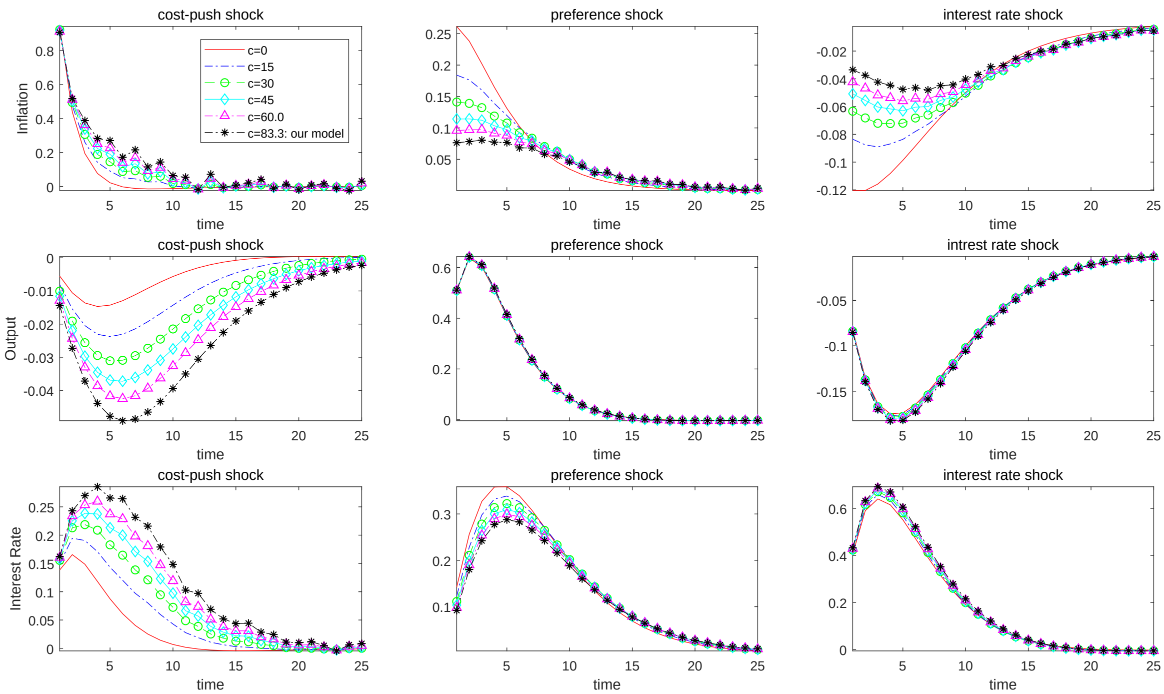
4.3 Impulse Response Functions

This section shows the impulse response functions (IRFs) for the proposed DSGE model, and the impact of the adjustment costs of prices, c, on the responses. The IRFs are generated using the estimates reported on Table 1, allowing the parameter c to vary from 0, corresponding to the standard NKPC with Calvo pricing, to our proposed DSGE with estimated value of $c = 83.3$. Figure 2 displays the responses of inflation, output gap, and interest rate to a one-standard deviation cost-push shock (first column), preference shock (second column), and monetary shock (third column).

As shown in the first column, the cost-push shock leads to an immediate increase in inflation regardless of the value of c. The response of inflation dies off more gradually as the value of c increases. The monetary authority raises the Federal Funds rate in response to higher inflation, which leads to a decrease in output gap. The shock has the largest impact on output gap after 6 quarters in our model, with the estimate of c is taken into account, while it has the largest effect after 3 quarters for the standard NKPC ($c = 0$). As shown in Figure 2, higher price adjustment cost implies as a response short-term interest rate that remains high for a considerable time period, yielding a large contraction in economic activity. Accordingly, larger c leads to a more persistent and gradual decline in output gap as a response to cost-push shock. This property of our model is similar to the one of the hybrid NKPC, which also predicts a persistent and positive deviation of inflation from its steady state in the face of the cost-push shock. The similarity is due to the fact that both models consider inflation persistence.

The impulse responses to a demand (preference) shock are shown in the second column. The shock drives up inflation, output gap, and the short-term interest rate. When the price adjustment cost is low, the impact of the shock on inflation is considerably larger. In contrast, the response of inflation in the proposed sticky inflation model is gradual and persistent, with the largest impact occurring 3 quarters later. This result arises from the fact that price setters not only change their prices infrequently, but also do not completely readjust their prices when the opportunity occurs. In the standard NKPC model ($c = 0$), as firms fully adjust prices in response to a demand shock, the impact on inflation is large and immediate due to the significant role of expectations in determining inflation: when a positive demand shock hits the economy, firms expect output to remain high for several quarters. Since inflation is determined by a discounted sum of current and expected future values of output gap, inflation rises substantially in response to the demand shock if there is no considerable cost of price adjustment.

Figure 2: Impulse Response Functions



Note: The estimated IRFs from our proposed DSGE model are the dashed lines with stars corresponding to $c = 83.3$, while the estimated IRFs for the standard NKPC with Calvo pricing are the solid lines with adjustment cost $c = 0$.

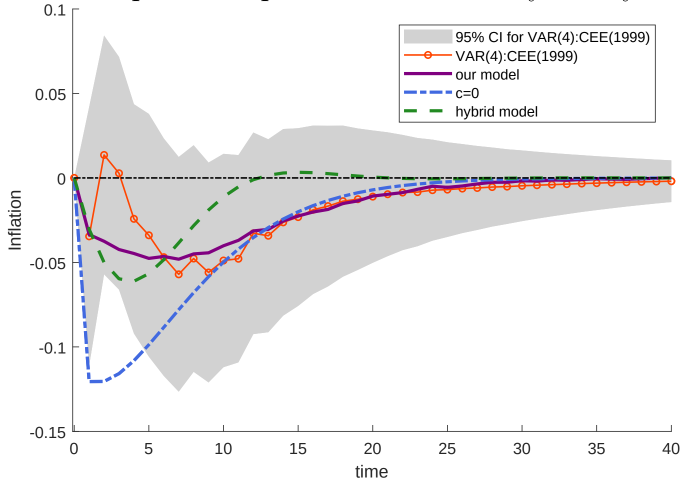
However, when firms face large adjustment costs regarding the size of price changes as in our model, the impact of inflation expectations on prices reduces sharply, leading to a gradual rather than an abrupt rise in inflation. The delayed and gradual response of inflation to a change in output gap is an interesting consequence of the proposed model, which considers both infrequent and incomplete price adjustment.

The third column shows the impact of a one-standard deviation monetary policy shock. It is well-known in the literature that the purely forward-looking NKPC with Calvo setting fails to generate a hump-shaped response of inflation to a monetary policy shock. As shown in the figure, the standard NKPC model ($c = 0$) yields an immediate and strong response of inflation to the contractionary monetary shock. By contrast, there is a delayed and gradual response of inflation to the policy shock in our model ($c = 83.3$), with the largest impact on inflation occurring after 7 quarters. Thus, our proposed model is more in accord with the persistence in inflation.

Figure 3 further compares the impact of a contractionary monetary policy shock in the estimated proposed DSGE model (solid line), with the standard NKPC with Calvo pricing (dash-dotted line), the hybrid NKPC of Smets and Wouters (2007, dashed line), and the VAR(4) model of Christiano, Eichenbaum, and Evans (CEE 1999, solid line with circles). We find that the delayed and hump-shaped response of inflation can be explained by incomplete and infrequent price adjustments in the proposed model, as does the hybrid NKPC model.[19] On the other hand, the standard NKPC model ($c = 0$) fails

[19]The hybrid NKPC model relies on the ad-hoc indexation assumption to account for inflation persistence, while our theory suggests that inflation persistence can be generated in a forward-looking framework when firms adjust their prices gradually in a staggered price setting.

Figure 3: Impulse Response to a Monetary Policy Shock



Note: The estimated IRFs from our proposed DSGE model is the solid line with dots corresponding to $c = 83.3$. The standard NKPC with Calvo pricing is the dashed line with adjustment cost $c = 0$. The IRF for the VAR (4) corresponds to the hybrid model from Christiano, Eichenbaum, and Evans (CEE 1999) and is the solid line with dots.

to account for the hump-shaped response of inflation and its impulse response function lies outside of the 95 percent confidence interval of the VAR(4) model. Thus, the standard NKPC is not supported by the empirical VAR model. The figure shows that the VAR(4) model predicts the maximum impact after seven quarters. Our proposed model also predicts the maximum impact of a contractionary monetary policy shock on inflation to be after seven quarters. The hybrid model impulse response displays a shorter impact time, with the maximum occurring after four quarters.

Our model has an amplification effect of cost-push shocks on inflation and a reduced impact of demand and monetary shocks. The predicted lower response of inflation to monetary shock in the hybrid NKPC model is somewhat similar to ours. This similarity is driven by the ability of the hybrid NKPC to generate sluggish movement of inflation in response to shocks. For example, in response to a demand (or expansionary monetary) shock, output positively deviates from its steady state for a considerable time. The standard NKPC with Calvo pricing predicts an immediate rise in inflation since firms are excessively forward-looking. Including a lagged inflation term to the NKPC prevents inflation from jumping from its steady state. Therefore, the response of inflation to the demand-side shocks is reduced.

4.4 Hump-Shaped Response and Alternative Quadratic Cost

This subsection studies whether the hump-shaped response of inflation in the face of a monetary shock is a consequence of the presence of lagged inflation in equation (14). In order to investigate this issue, we replace the price quadratic cost $\frac{c}{2}\left(\frac{\tilde{P}_{i,t}}{\tilde{P}_{i,t-j}}-1\right)^2 Y_t$ in equation (7), associated with changes in nominal price, with $\left(\frac{\tilde{P}_{i,t}/P_t}{\tilde{P}_{i,t-j}/P_{t-j}}-1\right)^2 Y_t$, associated with changes in real price. In this case, equation (9) is replaced with

$$E_t \sum_{k=0}^{\infty} (\theta\beta)^k \left[(\tilde{p}_{i,t}\tilde{X}_{t,k} - exp(e_{\pi,t})mc_{t+k})(\tilde{p}_{i,t}\tilde{X}_{t,k})^{-a} Y_{t+k}\right] - \frac{c}{2}\left(\frac{\tilde{p}_{i,t}}{\tilde{p}_{i,t-j}}-1\right)^2 Y_t \tag{22}$$

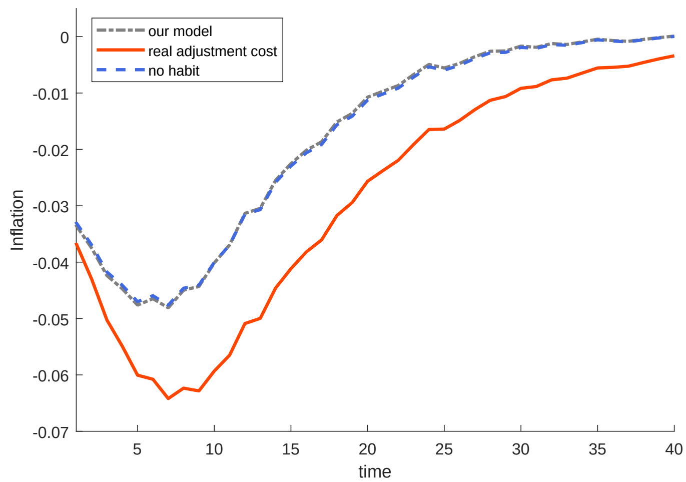
This assumption only eliminates the terms associated with current and lagged inflation from the objective function (9) keeping everything else unchanged. With that assumption, the inflation terms are also dropped from the aggregate optimal price of the firms (14), yielding

$$\hat{\tilde{p}}_{l_j,t} = \theta\beta E_t\left(\hat{\tilde{p}}_{l_j,t+1} + \left[\frac{a-1}{a-1+c\,(1-\theta\beta)}\right]\hat{\pi}_{t+1}\right) + \frac{(1-\theta\beta)\,(a-1)}{a-1+c\,(1-\theta\beta)}\,(\hat{mc}_t)$$

$$+\frac{c\,(1-\theta\beta)}{a-1+c\,(1-\theta\beta)}\left(\hat{\tilde{p}}_{l_j,t-j} - \theta\beta\hat{\tilde{p}}_{l_j,t-j+1}\right) + \epsilon_{\pi,t}. \tag{23}$$

We further investigate whether habit in consumption helps explain the hump-shaped response of inflation, by estimating the model for the case when the habit parameter h is zero.

Figure 4: Response of Inflation to Monetary Policy Shock



Note: The estimated IRFs from our proposed DSGE model is the dashed-dotted line. The IRF from our model without habit formation is the dashed line, and the IRF from our model with real adjustment cost is the solid line.

Figure 4 displays the response of inflation when a contractionary monetary shock hits the economy. The solid line is associated with the proposed DSGE model with real cost of price adjustment (rather than nominal cost price of adjustment), the dashed line is our DSGE model for the case of $h = 0$ (no habit), and the dashed-dotted line is our full proposed model with nominal adjustment cost and habit formation. As can be seen, imposing $h = 0$ does not change the response of inflation at all. In addition, we find that eliminating the terms of lagged inflation from equation (14) by assuming real cost of price adjustment also generates a hump-shaped response of inflation in response to a contractionary monetary shock.[20] These results show that the hump-shaped response of inflation to monetary shock in our model occurs when firms face real or nominal adjustment costs, and when consumers display or not habit persistence, indicating that this result is a consequence of incomplete price adjustment in a staggered price setting.

[20]Notice that the fundamental difference between (23) and our proposed NKPC (14) is whether the optimal price depends on lagged inflation.

4.5 Mechanism behind Endogenous Inflation Persistence

We further study how incomplete price adjustment generates inflation persistence endogenously. This is not easy to show given that the assumption of heterogeneous firms with respect to the time elapsed after their last price adjustment implies that it is not possible to derive a closed form solution for inflation dynamics. In order to get an insight on the mechanism endogenously generating inflation persistence, in this subsection we use a simplifying assumption that the firms resetting their prices face the same adjustment cost, $\frac{c}{2}\left(\tilde{P}_t/\tilde{P}_{t-1}-1\right)^2 Y_t$, instead of $\frac{c}{2}\left(\tilde{P}_{i,t}/\tilde{P}_{i,t-j}-1\right)^2 Y_t$. Our goal is to show that inflation persistence arises as a consequence of an interaction between infrequent and incomplete price adjustment. In this context, the firm chooses $\tilde{P}_t$ to maximize

$$E_t \sum_{k=0}^{\infty}(\theta\beta)^k \left[\frac{(\tilde{P}_t - mc_{t+k}P_{t+k})Y_{it+k}}{P_{t+k}}\right] - \frac{c}{2}\left(\frac{\tilde{P}_t}{\tilde{P}_{t-1}}-1\right)^2 Y_t \tag{24}$$

subject to the demand function described by equation (3). The assumption that the firms resetting prices face the same adjustment cost allows them to choose the same optimal price, delivering a closed-form solution for inflation dynamics. The first order condition is given by

$$E_t \sum_{k=0}^{\infty}(\theta\beta)^k \left[\tilde{X}_{tk}^{-a}\tilde{p}_t^{-a-1}Y_{t+k}\left((1-a)\tilde{p}_t\tilde{X}_{tk} + (a)mc_{t+k}\right)\right] - c\left[\frac{\tilde{p}_t}{\tilde{p}_{t-1}}\pi_t - 1\right]\frac{1}{\tilde{p}_{t-1}}\pi_t Y_t = 0 \tag{25}$$

where $\tilde{p}_t = \tilde{P}_t/P_t$. Log-linearization of the first order condition yields

$$E_t \sum_{k=0}^{\infty}(\theta\beta)^k \left[(\hat{\tilde{p}}_t + \hat{X}_{tk} - \hat{m}c_{t+k})\right] = \frac{c}{1-a}\left(\hat{\tilde{p}}_t - \hat{\tilde{p}}_{t-1} + \hat{\pi}_t\right). \tag{26}$$

Since log-linearization of equation (5) yields $\hat{\tilde{p}}_t = \frac{\theta}{1-\theta}\hat{\pi}_t$, the deviation of the optimal price from its previous one can be written as

$$\hat{\tilde{p}}_t - \hat{\tilde{p}}_{t-1} = [\theta/(1-\theta)][\hat{\pi}_t - \hat{\pi}_{t-1}]. \tag{27}$$

This equation reveals that the lagged optimal price introduces lagged inflation into the model. Plugging this into equation (26), rearranging the terms, and deleting the hat on the variables for convenience yields

$$\pi_t = \Lambda_f E_t \pi_{t+1} + \Lambda_l \pi_{t-1} + \lambda mc_t \tag{28}$$

where $\Lambda_f \equiv \eta/\tau$, $\Lambda_l \equiv \kappa/\tau$, $\lambda \equiv \zeta/\tau$, $\tau \equiv \theta(a-1) + c(1-\theta\beta)(1+\theta^2\beta)$, $\eta \equiv (a-1)\theta\beta + c(1-\theta\beta)\theta\beta$, $\kappa \equiv c(1-\theta\beta)\theta$, and $\zeta \equiv (a-1)(1-\theta)(1-\theta\beta)$. The NKPC equation (28) shows that the determinants of current inflation are the same as those from the hybrid NKPC of Gali and Gertler (1999), Christiano, Eichenbaum, and Evans (2005), and Smets and Wouters (2007). When the quadratic cost of price adjustment is zero, our model collapses into the standard NKPC shown in equation (17). In summary, this subsection shows how the two sources of price stickiness endogenously generate a lagged inflation term as a source of inflation persistence.[21]

4.6 Dynamic Correlation Between Output Gap and Inflation

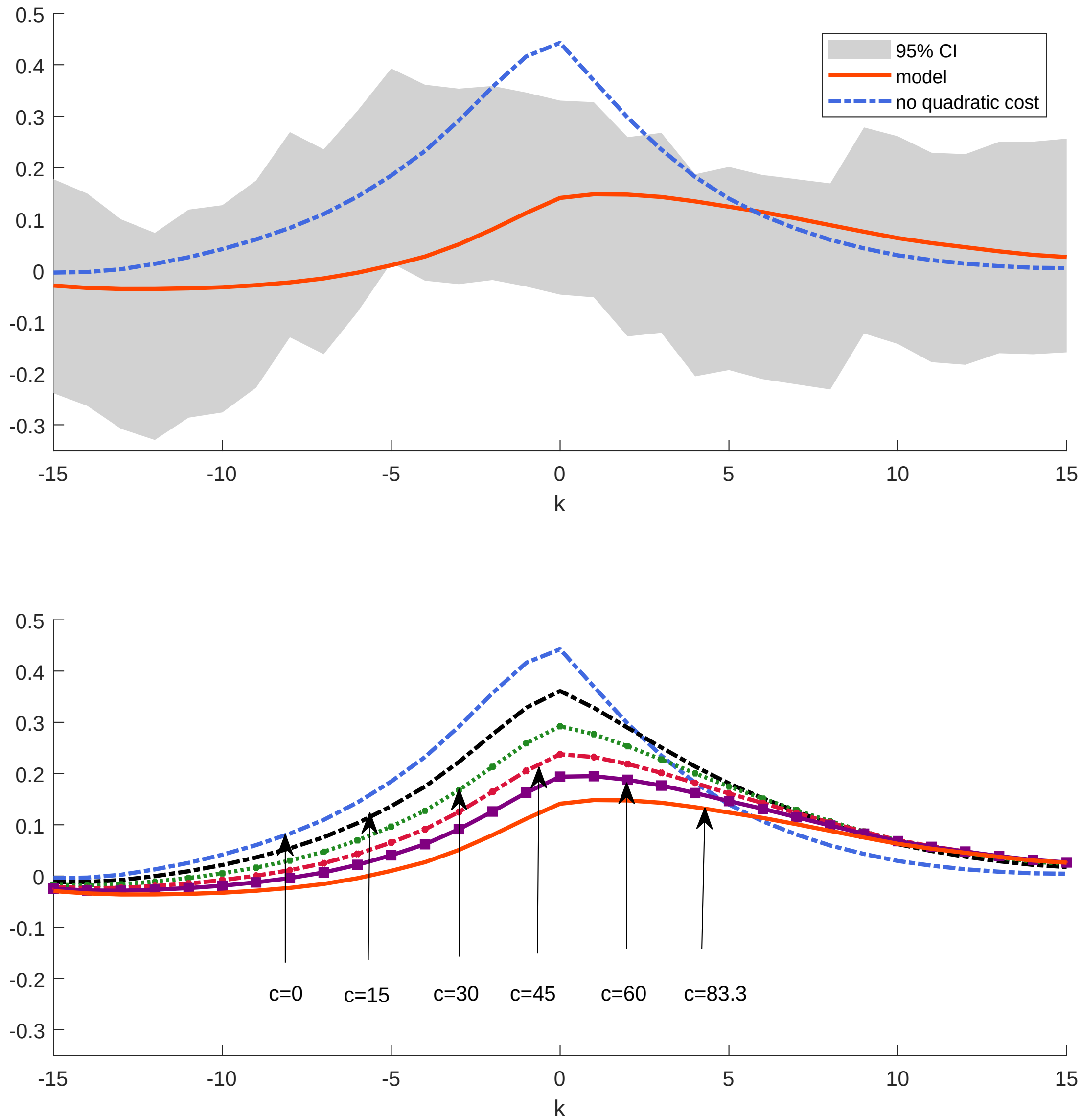
Taylor (1999) stresses that the ability to characterize the relationship between output gap and inflation is a criterion for the success of monetary models. This section examines whether the estimated model is able to generate the observed dynamic correlation between inflation and output gap, and the role of incomplete price adjustments in shaping the correlation structure.

The top panel of Figure 5 displays the dynamic correlation between inflation and output gap generated from our estimated DSGE model and from the standard NKPC with Calvo setting, with the 95 percent confidence interval from the VAR(4) model of Christiano, Eichenbaum, and Evans (CEE 1999). Our proposed model does a reasonable job describing this observed dynamic correlation between inflation and output gap, within the 95 percent empirical confidence interval. On the other hand, the model-implied dynamic correlation changes substantially when the quadratic price adjustment cost is restricted to zero. The standard NKPC model with Calvo pricing does a poor job in predicting the observed dynamic correlation. The contemporaneous correlation between these series implied by the standard NKPC ($c = 0$) model is abnormally high, in contrast with empirical evidence. This indicates that the assumption of incomplete price adjustments is important in accounting for the output-inflation dynamics.

The bottom panel in Figure 5 show how the overpredicted correlation can be reduced with the quadratic price adjustment cost. We simulate the DSGE model with the parameter c varying from zero as in the standard NKPC model to its estimated value ($c = 83.3$) in our proposed model, in order to generate the correlation between output gap and inflation. As can be seen, a rise in the price adjustment cost reduces the contemporaneous correlation, leading to a better fit of the data by the model. The intuition behind this result is that the increased cost of price adjustment causes a slower and more gradual response of inflation to demand and monetary shocks, even though the innovations lead to substantial movements in output gap, as shown in Figure 2. Once the three shocks are taken into account simultaneously, the estimated DSGE model predicts the weak, but still positive, contemporaneous correlation between output gap and inflation, due to the reduced response of inflation to the demand-side shocks. When a positive demand shock (or an expansionary monetary shock) hits the economy, forward-looking firms expect that future values of output gap will be positive for a considerable time. Therefore, firms that receive a random signal of price adjustment raise their prices. The impact of this expectation channel on prices is substantial in the standard NKPC with Calvo pricing in which prices are fully adjusted. By contrast, the demand (or monetary) shock has a limited impact on

[21] Once the quadratic price adjustment cost is measured with respect to real price as $\frac{c}{2}\left(\frac{\tilde{P}_t/P_t}{\tilde{P}_{t-1}/P_{t-1}} - 1\right)^2 Y_t$, the first order condition can be written as $E_t \sum_{k=0}^{\infty} (\theta\beta)^k \left[\tilde{X}_{tk}^{-a} \tilde{p}_t^{-a-1} Y_{t+k} \left((1-a)\tilde{p}_t \tilde{X}_{tk} + (a) mc_{t+k}\right)\right] - c\left[\frac{\tilde{p}_t}{\tilde{p}_{t-1}} - 1\right] \frac{1}{\tilde{p}_{t-1}} Y_t = 0$. In this case, the resulting Phillips curve can be written as $\pi_t = \Lambda_f^r E_t \pi_{t+1} + \Lambda_l^r \pi_{t-1} + \lambda^r mc_t$ where $\Lambda_f^r \equiv \eta/\tau$, $\Lambda_l^r \equiv \kappa/\tau$, $\lambda^r \equiv \zeta^r/\tau^r$, $\tau^r \equiv \theta(a-1) + c(1-\theta\beta)\theta(1+\theta\beta)$, $\eta^r \equiv (a-1)\theta\beta + c(1-\theta\beta)\theta^2\beta$, $\kappa^r \equiv c(1-\theta\beta)\theta$, and $\zeta^r \equiv (a-1)(1-\theta)(1-\theta\beta)$. When $\beta = 1$, we hold $\Lambda_f^r + \Lambda_l^r = 1$.

Figure 5: Dynamic Correlation Between Output Gap(t) and Inflation($t+k$)



Note: In the top panel, the solid line is the dynamic correlation from our proposed DSGE model. The dashed line is the standard NKPC with Calvo setting (no quadratic cost, $c = 0$).

prices in our sticky inflation model in which prices adjust slowly.[22] Our simulation exercise reveals that relatively small price changes to demand-side shocks are important features for the success of the model in matching the observed contemporaneous correlation.[23] This evidence indicates that the assumption of incomplete price adjustments is important in accounting for the output-inflation dynamics.

[22]Recall that our model implies an amplified response of inflation to supply shocks, as discussed in subsection 4.3.

[23]Gagnon and López-Salido (2014) report microeconomic evidence that there is small observed price changes to large demand shocks from U.S. supermarkets.

4.7 Size of Price Adjustments

Klenow and Malin (2010) find that price changes are large on average, but also there are many small price changes as well. Alvarez et al. (2016) document evidence on small and large price changes in the U.S. and France Consumer Price Index after correcting for measurement error. This section investigates whether the model of incomplete price adjustment has the ability to generate small and large price changes. We also explore how our model is different from other sticky price models such as the hybrid NKPC of Smets and Wouters (SW 2007), the NKPC with Rotemberg pricing, and the standard NKPC with Calvo pricing. The models are compared with respect to their implied distribution of price changes, i.e., their ability to generate small and large price changes.

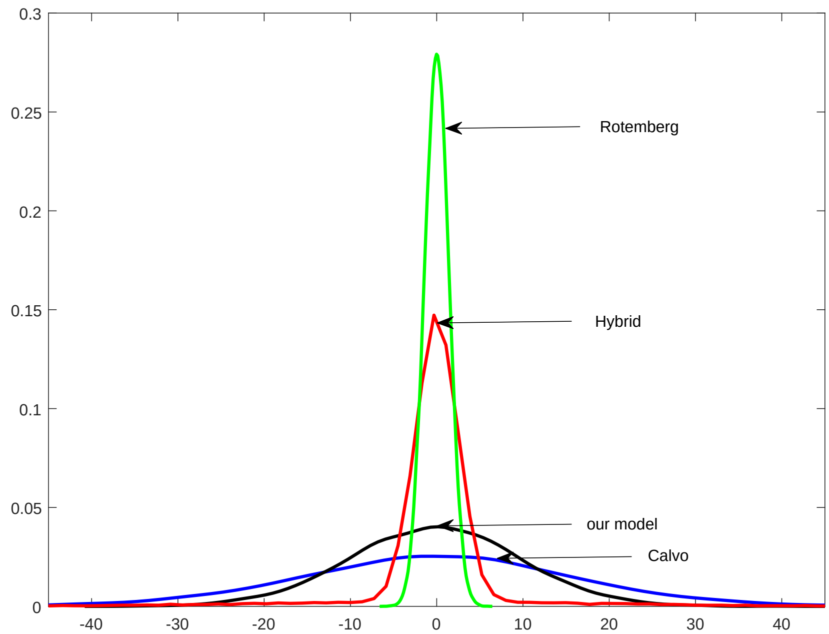
Table 2, Figure 6, and Figure 7 display the distribution of price changes of the different models for 1988:1 to 2005:1. This sample period is considered for comparison of our results to Klenow and Kryvtsov (KK 2008) and Nakamura and Steinsson (NS 2008) who use this sample to examine the size of price changes in the U.S. We also show results for the period 1983:1-2008:4 for comparison.[24]

Figure 6 plots the model-implied distributions of price changes. As can be seen, Rotemberg NKPC model generates more small price changes compared to the other models, with most price changes very close to the mean, and to each other. This is a result of the assumption that firms face adjustment costs that restrict full adjustment to optimal prices. On the other hand, the standard NKPC model with Calvo pricing implies a distribution with the largest variance in price changes. This is because in this model a fraction of firms optimize prices in a staggered manner that can lead to large price changes. Our proposed model and the hybrid NKPC model are in between these two cases. Even though both the hybrid model and our model are designed to generate inflation persistence, there is a fundamental difference between the models with respect to the size of price changes. As shown in the figure, our proposed sticky inflation model produces more small price changes than the standard NKPC with Calvo pricing, and larger price changes than the hybrid NKPC or Rotemberg NKPC models.

Table 2 reports more features of the estimated models' distribution along with the observed data as found in Klenow and Kryvtsov (KK 2008) and Nakamura and Steinsson (NS 2008). These papers use a large database of the U.S. Consumer Price Index collected by the Bureau of Labor Statistics (BLS), which contains the prices of thousands of individual goods and services. Klenow and Kryvtsov (2008) find that in the U.S. 44% of consumer regular price changes are smaller than 5 percent, 25% are smaller than 2.5 percent, and 12% are smaller than 1 percent, in absolute value. Our proposed model has the closest fit with the observed distribution of price changes. It estimates that 38% of price changes are smaller than 5 percent, 20% are smaller than 2.5%, and 8% are smaller than 1 percent, in absolute value. On one side, Rotemberg NKPC predicts that 100% of prices changes are smaller than 5 percent. On the other, the standard NKPC with Calvo pricing estimates that only 25% of price changes are smaller than 5%. The hybrid NKPC model results are closer to Rotemberg NKPC, predicting that 87% of the

[24] Inflation fluctuations were more stable during the period studied by Klenow and Kryvtsov (2008) and Nakamura and Steinsson (2008) (which roughly coincides with Greenspan's chairmanship at the Federal Reserve) than in the earlier period. We simulate all models with the estimated standard deviations of the shocks matching the *observed* standard deviation of inflation for the 1988:1-2005:1 period. We additionally report the distribution of price changes but based on the *estimated* standard deviations of the shocks for the 1983:1-2008:4 period for comparison.

Figure 6: Distributions of Price Changes



price changes are smaller than 5%. Thus, both the Rotemberg and the hybrid NKPC model estimates of small (large) price changes are substantially above (below) what is found in the data, while the standard NKPC with Calvo pricing predicts substantially more large price changes than observed. Our model generates more small price changes than the Calvo model due to the presence of the quadratic price adjustment cost and less large price changes than Rotemberg NKPC model due to the staggering price assumption. The results corroborate the importance of infrequent price adjustment in generating many large price changes. Most of the price changes are very small in the hybrid NKPC and Rotemberg models, consistent with their implication that prices are adjusted continuously. The models that imply continuous price changes do not account for observed price changes at all. Our findings reveal that our model and, to some extent the Calvo NKPC model, are successful in generating many small price changes as observed in microeconomic data. On the other hand, Calvo NKPC model overpredicts large prices changes compared to the data.

Table 2 also reports the mean and median absolute price changes. The proposed model implies that the average (median) size of price changes is 8 percent (7 percent), while the NKPC with Calvo pricing generates an average (median) size of 13 percent (11 percent). These estimations are broadly consistent with the observed data. Klenow and Kryvtsov (2008) report that a mean (median) change in regular prices is 11 percent (10 percent) in absolute value. Nakamura and Steinsson (2008) report a median size of 8.5 percent for U.S. consumer goods prices. For the Euro area Dhyne et al. (2005) find that the observed average value of consumer price change is 9 percent. On the other hand, most of the price changes are very small in the hybrid NKPC and Rotemberg models, consistent with their implication that prices are adjusted continuously. The hybrid NKPC and Rotemberg models predict that the average size of price changes is 4 percent and 1 percent, respectively. This simulation exercise

Table 2: Size of Price Changes - Models and Data

Period	Data/Models	$\lvert\Delta P_i\rvert < 1\%$	$\lvert\Delta P_i\rvert < 2.5\%$	$\lvert\Delta P_i\rvert < 5\%$	Mean $\lvert\Delta P_i\rvert$	Median$\lvert\Delta P_i\rvert$
Data	KK posted prices	11.3	23.4	39.8	14.0	11.5
1988:1-2005:1	KK regular prices	12.1	25.4	44.3	11.3	9.7
	NS PPI prices					7.7
	NS CPI prices					8.5
Models	Proposed Model	8.4	20.3	38.5	8.0	6.7
1988:1-2005:1	Std. Calvo NKPC	4.7	12.6	25.5	12.7	10.6
	SW Hybrid NKPC	2.9	62.5	87.2	3.7	1.9
	Rotemberg NKPC	51.8	92.2	100	1.1	0.96
Models	Proposed model	7.1	17.3	33.2	9.4	6.6
1983:1-2008:4	Std. Calvo NKPC	3.4	9.4	19.4	16.9	10.5
	SW Hybrid NKPC	22.2	50.2	79.0	4.9	1.6
	Rotemberg NKPC	40.3	81.3	99.2	1.5	97.0

Note: KK stands for Klenow and Kryvtsov (2008), NS for Nakamura and Steinsson (2008), and SW for Smets and Wouters (2007). CPI is the U.S. Consumer Price Index and PPI is the U.S. Production Price Index. $|\Delta P_i|$ is the absolute size of price changes. Posted prices include both regular and sales prices. Both KK (2008) and NS (2008) investigate micro-data using the sample 1988:1 to 2005:1.

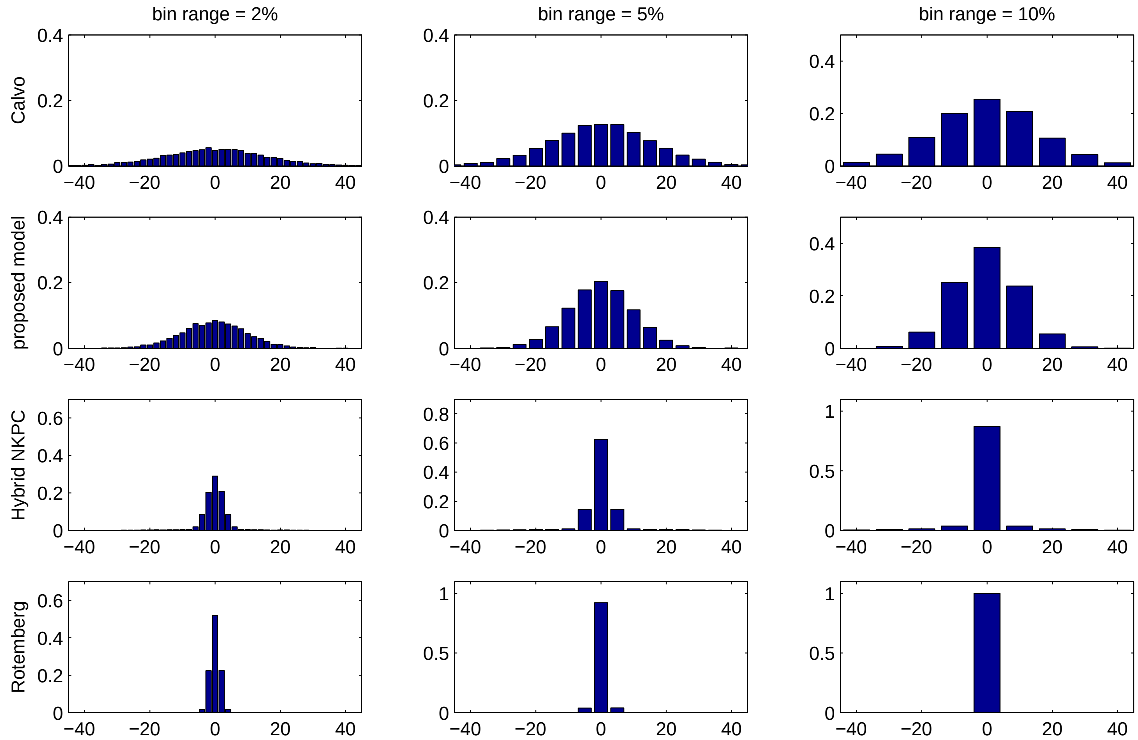
reveals that the hybrid NKPC and Rotemberg models fall short in matching the average size of price changes observed in microeconomic data. The standard Calvo fits well the mean and median size of price changes but misses substantially regarding the variance of price changes. We further examine the 1983:1-2008:4 period, which includes periods of less inflation stability. We find that the estimated size of price changes increases for all models. However, the overall shape of the distribution of price changes does not change with the extended sample period (Table 2).

In summary, our findings reveal that our model with infrequent price changes performs better than the hybrid NKPC and the NKPC with Rotemberg pricing in generating large price changes, and better than the Calvo NKPC model in generating many small price changes as observed in microeconomic data. This evidence shows that the model has the ability to generate large price changes although the convex cost of price adjustment is embedded in the NKPC model with Calvo pricing.[25] As discussed earlier, the combination of staggered price contracts and convex costs amplifies the impact of cost-push shocks to inflation while it reduces the response of inflation to demand and monetary shocks. Thus, cost-push shocks produce large price changes, whereas demand and monetary shocks generate small price changes. Infrequent price adjustment also helps generating large price changes. These are the reasons behind the ability of the proposed model in generating large price changes. In contrast to the proposed model, the

[25] Golosov and Lucas (2007) point out that a standard menu cost model is not able to generate small price changes in the micro-data when the model is made to match the size of price changes, about 10 percent on average. This issue is closely related to the (in)ability of menu cost models to produce non-neutrality of money (e.g., Golosov and Lucas 2007 and Midrigan 2009). Due to this shortcoming, the menu cost model is extended to have either random menu costs or economics of scale in adjusting prices faced by multi-product firms so that they have the ability to produce many small price changes (Klenow and Kryvtsov 2008, and Midrigan 2009, cite). The previous work has focused on the ability of menu cost models to match the distribution of price changes driven by idiosyncratic shocks. Our model differs from the menu cost models in that small price changes are produced due to the price adjustment cost that increases with the size of price changes. Additionally, our paper focuses on macroeconomic shocks such as cost-push shocks, monetary shocks, and demand shocks, while the menu cost models focus on idiosyncratic shocks. One similarity between our model and the extended menu cost models is that large price changes are associated with infrequent price adjustments. In Midrigan (2009), a multi-product firm faces a single menu cost of adjusting the prices of goods. When goods-specific shocks hit the firm, some goods' prices are likely to be close from their optimal prices while others are likely to be far from their optimal prices. The prices of the multi-product firm are adjusted together at any point in time due to economics of scale. Thus, the model is able to produce small and large price changes.

standard Calvo NKPC model creates relatively large price adjustments in response to demand shocks and small price adjustments in response to cost shocks.[26]

Figure 7: Distribution of Price Changes: 1988:1-2005:1



Notes: The value of θ is set at our estimate in the Calvo, hybrid NKPC, and our models. The value of c is 83.3 in our model. The value of c is chosen for the Rotemberg model to have the same slope as the NKPC with Calvo pricing. It results in $c = 284.7$. The remaining parameters and standard deviations of shocks are set at the same values across models.

4.8 Robustness of the Results

This section studies the robustness of our estimation results to alternative series and across various sample periods (1960:1-1979:4, 1983:1-2008:4, and 1960:1-2008:4).We examine the results when inflation in level and detrended inflation are considered.[27] We also employ alternative detrending methods for real GDP to obtain output gap, since as emphasized by Gali and Gertler (1999) nonstationary potential real GDP is observed with considerable measurement errors. Real GDP is detrended using the Congressional Budget Office's (CBO) potential real GDP and using Christiano-Fitzgerald's (CF) one-sided filter, in addition to Hodrick–Prescott (HP) two-sided filter applied in the previous subsections.[28]

Table 3 shows the estimates of the key parameters from the proposed DSGE model with staggering

[26] Gagnon and López-Salido (2014) report microeconomic evidence that observed price changes to large demand shocks from U.S. supermarkets are small.

[27] Inflation is detrended using trend inflation obtained from the time-varying Bayesian VAR model of Cogley and Sbodorne (2008) using their code.

[28] Since there is no variation of technology, the output gap defined as the deviation of output from its potential level is equivalent to output in the model. This approach allows us to estimate the DSGE model with one- and two-sided filtered output as well as the CBO's output gap measure to test for robustness of our results. Justiano and Primiceri (2008) show that the "DSGE-based output gap captures cyclical fluctuations very well, closely resembling HP-detrended output and the CBO output gap in particular."

Table 3: Likelihood Estimates of Key Parameters: Proposed Model with Inflation Level and Different Measures of Output Gap

Detrended Output	Param.	1960:1-1979:4 Post. Mean	1960:1-1979:4 95% Conf. Interval	1983:1-2008:4 Post. Mean	1983:1-2008:4 95% Conf. Interval	1960:1-2008:4 Post. Mean	1960:1-2008:4 95% Conf. Interval
Bench. HP	c	62.6	[25.6, 99.0]	83.3	[50.0, 113.3]	64.8	[35.3, 93.8]
	θ	0.56	[0.33, 0.76]	0.88	[0.78, 0.92]	0.86	[0.81, 0.91]
CBO	c	66.0	[30.2, 100.9]	86.1	[56.8, 114.7]	63.0	[30.0, 95.4]
	θ	0.55	[0.33, 0 76]	0.89	[0.86, 0 92]	0.86	[0.78, 0.91]
CF	c	67.0	[34.7, 101.9]	81.4	[47.6, 110.6]	37.8	[13.1, 67.3]
	θ	0.55	[0.33, 0.79]	0.87	[0.80, 0.92]	0.68	[0.59, 0.85]

Note: In the previous subsections the proposed model was estimated using inflation level and output gap detrended using the HP filter for the periods 1988:1-2005:4 and 1983:1-2008:4

price and quadratic price adjustment cost using the detrended real GDP, inflation level, and the Federal Funds rate across the different sample periods. First, we notice that the estimates of the Calvo parameter θ and the Rotemberg coefficient do not change much across different measures of output gap for the periods that exclude 1980-1982. Comparing the results over different output gap measures and and samples, consistently indicate that firms face the quadratic price adjustment cost in addition to changing their prices in a staggered fashion. Accordingly, 95% of the posterior means on the Calvo and Rotemberg parameters are substantially away from zero.[29]

However, the estimates change somewhat over the samples. In particular, posterior mean estimates of the Calvo coefficient θ are lower for the period pre-1980, between 0.55-0.56, compared to the period post-1983 (0.87-0.89) and to the whole sample (0.68-0.86). A lower Calvo coefficient implies a higher frequency of price adjustment, which is consistent with high inflation periods. [30]

The posterior mean estimates of the quadratic cost, c, are higher during the Great Moderation period (1983:1-2008:4) compared to the period pre-1983 or the whole sample. This finding is in accord with the evidence that prices are more sticky during the stable period, since higher adjustment cost discourages firms from changing their prices.

We re-estimate the proposed DSGE model using detrended inflation to examine whether trend inflation could be a source of inflation persistence. The estimates of the key parameters are reported in Table 4. We find that the estimated mean of θ and c are similar to those reported in Table 3 as well as the patterns across samples, indicating that detrending inflation does not change our results. That is, price changes are less frequent during the Great Moderation period (higher Calvo parameter), compared to the periods that include high inflation. Additionally, Rotemberg adjustment coefficient is higher during the Great Moderation period.

In summary, the estimations support empirical evidence that the combination of both Calvo price

[29] Although we do not report here, we find that the introduction of the price adjustment cost into a staggered pricing setting always delivers higher likelihoods than the NKPC with Calvo pricing across samples.

[30] Note that a direct comparison of the estimated average duration between price changes and micro-data can be misleading, given that our model assumes heterogeneity in the frequency of price change across firms. We have estimated a version of the model as described in subsection 4.5 in which firms are homogeneous with respect to the duration of price changes. In this case, the Calvo parameter is 0.76, which is in between the estimated values for the sub-samples found in the heterogeneous firms model.

setting and Rotemberg adjustment cost model are important in yielding a good adherence of the model to the data, with both playing a role in determining changes in prices (both estimates are significantly away from zero).

Table 4: Likelihood Estimates of Key Parameters: Proposed Model with Detrended Inflation and Different Measures of Output Gap

Detrended Output	Param.	1960:1979:4 Post. Mean	1960:1979:4 95% Conf. Interval	1983:1-2008:4 Post. Mean	1983:1-2008:4 95% Conf. Interval	1960:1-2008:4 Post. Mean	1960:1-2008:4 95% Conf. Interval
Bench. HP	c	67.1	[31.7, 103.2]	76.4	[49.5, 105.2]	68.7	[39.6, 96.7]
	θ	0.57	[0.36, 0.78]	0.87	[0.81, 0.91]	0.87	[0.83, 0.92]
CBO	c	67.3	[32.4, 105.0]	84.4	[55.4, 111.5]	75.0	[42.7, 103.4]
	θ	0.57	[0.34, 0.79]	0.90	[0.85, 0 94]	0.89	[0.85, 0.92]
CF	c	62.7	[25.2, 99.4]	80.0	[51.7, 108.5]	70.9	[43.5, 100.3]
	θ	0.59	[0.38, 0.79]	0.88	[0.84, 0.92]	0.87	[0.82, 0.91]

Note: In the previous sections the proposed model was estimated using inflation level and output gap detrended using the HP filter (benchmark) for the periods 1988:1-2005:4 and 1983:1-2008:4

One might be interested in whether the model is able to match the volatility of key macroeconomic variables across the sample periods. Table 5 reports the observed standard deviations of inflation, HP-filtered output, and the Federal Funds rate and the model-implied counterparts. The model matches well the observed volatility of inflation and output gap across different samples. The standard deviation of the short-term interest rate is underpredicted in the model.[31]

5 Conclusion

The standard New Keynesian Phillips curve with Calvo (1983) pricing and the quadratic adjustment cost model of Rotemberg (1982) are extensively used in the monetary policy literature. However, standard NKPC models have been criticized due to the failure to generate inflation persistence. Although the price level responds sluggishly to shocks in these models, the inflation rate does not. In addition, in these models monetary policy shocks do not cause a delayed and gradual effect on inflation as observed in the data. One of the most popular ways to generate inflation persistence in the literature is with indexation models (hybrid NKPC), which assume that a fraction of firms reset their prices by automatic indexation. However, the indexation models (hybrid NKPC) have been criticized for the lack of microfoundations backing the introduction of the lagged inflation term in the Phillips curve.

[31] This underprediction might be related to the fact that the model does not consider the Fed's time-varying inflation target.

Table 5: Standard Deviation of Macroeconomic Variables

Sample	Data $\sigma(\pi)$	Data $\sigma(y)$	Data $\sigma(i)$	Model $\sigma(\pi)$	Model $\sigma(y)$	Model $\sigma(i)$
1960-1979	2.76	1.77	2.63	2.59	1.77	2.29
1983-2008	0.97	1.17	2.50	1.16	1.37	2.00
1960-2008	2.37	1.53	3.28	2.04	1.52	2.49

This paper proposes a model in which a lagged inflation term is endogenously generated from the optimizing behavior of forward-looking firms, which face two sources of price rigidities related to both the inability to change prices frequently and the cost of sizable adjustments. Our results show evidence of price stickiness due to both the size and frequency of price adjustments. The proposed sticky inflation model satisfactorily explains the presence small and large price change, the impulse response functions of variables, and the observed dynamic behavior between output gap and inflation. Our model provides structural interpretations of inflation dynamics. In particular, the model provides a theoretical foundation and interpretation for the resulting inertial inflation and a delayed, gradual impact of demand and monetary shocks on inflation. Such an effect is produced because even when price changes at discrete time intervals, they are only partially adjusted. These results indicate that the proposed sticky inflation model with both staggered prices and costs of adjustment is in closer agreement with the data than the NKPC model with Calvo price setting, NKPC with Rotemberg adjustment costs, or hybrid NKPC models.

References

[1] Adam, Klaus & Mario Padula. 2011. “Inflation Dynamics And Subjective Expectations In The United States.” Economic Inquiry, vol. 49(1): 13-25.

[2] Alvarez, Luis J. 2008. “What Do Micro Price Data Tell Us on the Validity of the New Keynesian Phillips Curve?” The Open-Access, Open-Assessment E-Journal, 2(19): 1-35.

[3] Alvarez, Luis J., Emmanuel Dhyne, Marco M. Hoeberichts, Claudia Kwapil, Herve Le Bihan, Patrick Lunnemann, Fernando Martins, Roberto Sabbatini, Harald Stahl, Philip Vermeulen, and Jouko Vilmunen. 2006. “Sticky Prices in the Euro Area: A Summary of New Micro Evidence.” Journal of the European Economic Association, 4 (April-May): 575-584.

[4] Alvarez, Luis J., Herve Le Behan, and Francesco Lippi. 2016. “The Real Effects of Monetary Shocks in Sticky Price Models: A Sufficient Statistic Approach.” American Economic Review. 106(10):2817-2851.

[5] Angeloni, Ignazio, Luc Aucremanne, Michael Ehrmann, Jordi Gali, Andrew Levin, and Frank Smets. 2006. “New Evidence on Inflation Persistence and Price Stickiness in the Euro Area: Implications for Macro Modeling.” Journal of the European Economic Association, 4(2-3): 562-574.

[6] Benati, Luca. 2008. “Investigating Inflation Persistence Across Monetary Regimes.” Quarterly Journal of Economics, 123(3): 1005-1060.

[7] Bils, Mark, Peter J. Klenow, and Benjamin A. Malin. 2012. “Reset Price Inflation and the Impact of Monetary Policy Shocks.” American Economic Review, 102(6): 2798-2825.

[8] Blinder, Alan S., Elie R. D. Canetti, David Lebow, and Jeremy B. Rudd. 1998. “Asking About Prices: A New Approach to Understand Price Stickiness.” New York: Russell Sage Foundation.

[9] Burstein, Ariel, and N. Jaimovich. 2012. “Understanding Movements in Aggregate and Product-Level Real Exchange Rates.” Working Paper, UCLA.

[10] Brock, W., W. Dechert, A. Scheinkman, and B. LeBaron. 1996. “A Test for Independence Based on the Correlation Dimension,” Econometric Reviews,15(3): 197-235.

[11] Calvo, Guillermo A. 1983. “Staggered Prices in a Utility-Maximizing Framework”. Journal of Monetary Economics, 12(3): 383-98.

[12] Carroll, Christopher. 2003. “Macroeconomic Expectations of Households and Professional Forecasters”. Quarterly Journal of Economics, 118(1): 269-98.

[13] Cho, Seonghoon, and Antonio Moreno. 2006. “A Small-Sample Study of the New-Keynesian Macro Model.” Journal of Money, Credit, and Banking, 38(6):1461-1481.

[14] Christiano, Lawrence J., Martin Eichenbaum, and Charles L. Evans. 1999. "Monetary policy shocks: What Have We Learned and to What End?" Handbook of Macroeconomics, Chapter 2, 1(A): 65-148.

[15] Christiano, Lawrence J., Martin Eichenbaum, and Charles L. Evans. 2005. "Nominal Rigidities and the Dynamic Effects of a Shock to Monetary Policy." Journal of Political Economy, 113(1): 1-45.

[16] Clarida, Richard H., Jordi Gali, and Mark Gertler. 2000. "Monetary Policy Rules and Macroeconomic Stability: Evidence and Some Theory." Quarterly Journal of Economics, 115(1): 147-180.

[17] Cogley, Timothy, and Argia Sbordone. 2008. "Trend Inflation, Indexation and Inflation Persistence in the New Keynesian Phillips Curve." American Economic Review, 98(5): 2101-2126.

[18] Coibion, Olivier. 2010. "Testing the Sticky Information Phillips Curve." The Review of Economics and Statistics, 92(1): 87-101.

[19] De Michelis, A. and M. Iacoviello. 2016. "Raising an Inflation Target: The Japanese Experience with Abenomics," European Economic Review, 88, September, 67-87.

[20] Dhyne, Emmanuel, Luis J. Alvarez, Herve Le Bihan, Giovanni Veronese, Daniel Dias, Johannes Hoffmann, Nicole Jonker, Patrick Lunnemann, Fabio Rumler, Jouko Vilmunen. 2005. "Price Setting in the Euro Area: Some Stylized Facts from Individual Consumer Price Data." European Central Bank Working Paper, No. 524.

[21] Eichenbaum, Martin and Terry Fitzgerald. 2003. "The Band Pass Filter ." International Economic Review, 44(2):435-465.

[22] Eichenbaum, Martin and Fisher, Jonas D.M., 2007. "Estimating the frequency of price re-optimization in Calvo-style models." Journal of Monetary Economics, Elsevier, 54(7): 2032-2047.

[23] Eichenbaum, Martin and Nir Jaimovich, and Sergio Rebelo. 2011. "Reference Prices and Nominal Rigidities." American Economic Review, 101(1): 242-272.

[24] Fabiani, Silvia, Martine Druant, Ignacio Hernando, Claudia Kwapil, Bettina Landau, Claire Loupias, Fernando Martins, Thomas Y. Matha, Roberto Sabbatini, Harald Stahl, and Ad C. J. Stokman. 2005. "The Pricing Behavior of Firms in the Euro Area: New Survey Evidence." Working Paper Series, 535, European Central Bank.

[25] Fitzgerald, Doireann, and Stefanie Haller. 2012. "Pricing-to-Market: Evidence From Plant-Level Prices," Working Paper, Stanford University.

[26] Fuhrer, Jeffrey C., and George R. Moore. 1995. "Inflation Persistence." Quarterly Journal of Economics, 110(1): 127-59.

[27] Fuhrer, Jeffrey C. 2000. "Habit Formation in Consumption and Its Implications for Monetary Policy Models." American Economic Review, 90(3): 367-390.

[28] Gagnon, Etienne, and David Lopez-Salido. 2014. "Small Price Responses to Large Demand Shocks." Finance and Economics Discussion Series 2014-18, Board of Governors of the Federal Reserve System.

[29] Gali, Jordi, and Mark Gertler. 1999. "Inflation Dynamics: A Structural Econometric Analysis." Journal of Monetary Economics, 44(2): 195-222.

[30] Gali, J., Gertler, M. and D. Lopez-Salido. 2001. "European Inflation Dynamics." European Economic Review, 45, 1237-1270.

[31] Gopinath, G., O. Itskhoki, and R. Rigobon. 2010. "Currency Choice and Exchange Rate Pass-through." American Economic Review, 100(1): 304-336.

[32] Golosov, M. and R.E. Lucas Jr. 2007. "Menu Costs and Phillips Curves," Journal of Political Economy 115(2): 171-199.

[33] Justiniano, Alejandro and Primiceri, Giorgio E. 2008. "Potential and Natural Output." NBER working paper No. 17071.

[34] Kara, Engin. 2015. "The Reset Inflation Puzzle and the Heterogeneity in Price Stickiness." Journal of Monetary Economics, 76: 29-37.

[35] Kimball, Miles Spencer. 1995. "The Quantitative Analytics of the Basic Neomonetarist Model." Journal of Money, Credit and Banking, 27(4): 1241-1277.

[36] Klenow, P. J., and J. L. Willis. 2006. "Real Rigidities and Nominal Price Changes." Working Paper No. RWP06-03, Federal Reserve Bank of Kansas City.

[37] Klenow, P. J. and J. L. Willis. 2007. "Sticky Information and Sticky Prices." Journal of Monetary Economics, 54(Supplement 1): 79-99.

[38] Klenow, Peter J. & Malin, B. A., 2010. "Microeconomic Evidence on Price-Setting," Handbook of Monetary Economics, in: Benjamin M. Friedman & Michael Woodford (ed.), Handbook of Monetary Economics, edition 1, volume 3, chapter 6: 231-284.

[39] Klenow, Peter J. and Oleksiy Kryvtsov. 2008. "State-Dependent or Time-Dependent Pricing: Does It Matter for Recent US Inflation?" Quarterly Journal of Economics, 123(3): 863-904.

[40] Kozicki, Sharon and Peter A. Tinsley. 2002. "Dynamic Specifications in Optimizing Trend-Deviation Macro models." Journal of Economic Dynamics and Control, 26(9): 1585-1611.

[41] Mankiw, N. Gregory, and Ricardo Reis. 2002. "Sticky Information Versus Sticky Prices: A Proposal to Replace the New Keynesian Phillips Curve." Quarterly Journal of Economics, 117(4): 1295-1328.

[42] Nakamura, Emi and Jón Steinsson. 2008. "Five Facts About Prices: A Reevaluation of Menu Cost Models." Quarterly Journal of Economics, 123(4): 1415-1464.

[43] Nakamura, Emi and Jón Steinsson. 2013. "Price Rigidity: Microeconomic Evidence and Macroeconomic Implications." Annual Review of Economics, 5: 133-163.

[44] Nelson, Edward. 1998. "Sluggish Inflation and Optimizing Models of the Business Cycle." Journal of Monetary Economics, 42(2), 303-322.

[45] Nilsson, R. and G. Gyomai. 2011. "Cycle Extraction: A Comparison of the Phase-Average Trend Method, the Hodrick-Prescott and Christiano-Fitzgerald Filters." OECD Statistics Working Papers , 2011/04, OECD Publishing.

[46] Nunes, R. 2010. "Inflation Dynamics: The Role of Expectations." Journal of Money, Credit and Banking 42(6): 1161-1172.

[47] Ravenna, F. and C. Walsh. 2006. "Optimal Monetary Policy and the Cost Channel," Journal of Monetary Economics, 53, 2, 199-216.

[48] Roberts, John M. 2006. "How Well Does the New Keynesian Sticky-Price Model Fit the Data?" Contributions to Macroeconomics, 5(1):ISSN 1534-6005

[49] Rotemberg, Julio J. 1982. "Sticky Prices in the United States." Journal of Political Economy, 90(6): 1187-1211.

[50] Rotemberg, Julio J. and Michael Woodford. 1992. "Oligopolistic Pricing and the Effects of Aggregate Demand on Economic Activity." Journal of Political Economy, 100(6): 1153-1207.

[51] Rotemberg, Julio J. 2005. "Customer Anger at Price Increases, Changes in the Frequency of Price Adjustment and Monetary Policy" Journal of Monetary Economics, 52(4): 829-52.

[52] Rudd, Jeremy, and Karl Whelan. 2005. "New Tests of the New-Keynesian Phillips Curve." Journal of Monetary Economics, 52(6): 1167-1181.

[53] Rudd, Jeremy, and Karl Whelan. 2006. "Can Rational Expectations Sticky-Price Models Explain Inflation Dynamics?" American Economic Review, 96(1): 303-320.

[54] Rudd, Jeremy, and Karl Whelan. 2007. "Modeling Inflation Dynamics: A Critical Review of Recent Research." Journal of Money, Credit and Banking, 39(1): 155-170.

[55] Sbordone, Argia M. 2007. "Inflation Persistence: Alternative Interpretations and Policy Implications." Journal of Monetary Economics, 54(5): 1311-1339.

[56] Smets, Frank, and Rafael Wouters. 2003. "An Estimated Dynamic Stochastic General Equilibrium Model of the Euro Area." Journal of the European Economic Association, 1(5): 1123-1175.

[57] Smets, Frank, and Rafael Wouters. 2007. "Shocks and Frictions in US Business Cycles: A Bayesian DSGE Approach." American Economic Review, 97(3): 586-606.

[58] Steinsson, Jon. 2003. “Optimal Monetary Policy in an Economy with Inflation Persistence.” Journal of Monetary Economics, 50(7): 1425-1456.

[59] Taylor, John B. 1979. “Staggered Wage Setting in a Macro Model.” American Economic Review, Papers and Proceedings, 69(2): 108-113.

[60] Taylor, John B. 1980. “Aggregate Dynamics and Staggered Contracts.” Journal of Political Economy, 88(1): 1-23.

[61] Taylor, John B. 1999. “Staggered Price and Wage Setting in Macroeconomics.” Handbook of Macroeconomics, North-Holland Elsevier, 1, Part 2, 1009-1050.

[62] Vermeulen, Philip, Daniel Dias, Maarten Dossche, Erwan Gautier, Ignacio Hernando, Roberto Sabbatini, Harald Stahl. 2007. “Price Setting in the Euro Area: Some Stylised Facts from Individual Producer Price Data and Producer Surveys.” European Central Bank Working Paper, 727.

[63] Walsh, Carl E. 2003. Monetary Theory and Policy, ed. 2, The MIT Press.

[64] Woodford, Michael. 1996. “Loan Commitments and Optimal Monetary Policy.” Journal of Monetary Economics, 37(3): 573-605.

[65] Woodford, Michael. 2007. “Interpreting Inflation Persistence: Comments on the Conference on Quantitative Evidence on Price Determination.” Journal of Money, Credit and Banking, 39(s1): 203-210.

[66] Yun, Tack. 1996. Nominal Price Rigidity, Money Supply Endogeneity, and Business Cycles.” Journal of Monetary Economics, 37(2): 345-370.

[67] Zbaracki, Mark J., Mark Ritson, Daniel Levy, Shantanu Dutta, and Mark Bergen. 2004. “Managerial and Customer Costs of Price Adjustment: Direct Evidence from Industrial Markets.” Review of Economics and Statistics, 86(2): 514-533.