How Does the Phillips Curve Slope Relate to Repricing Rates?

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In sticky price models, the Phillips curve slope depends positively on the probability of price adjustment. I test this implication using a series for the empirical frequency of price adjustment. I find that empirically, the Phillips curve slope does depend positively on the repricing rate. My results support the implication from New Keynesian theory with Calvo pricing that the Phillips curve slope is a convex function of the repricing rate. However, at all observed values of the price adjustment frequency, the empirical Phillips curve is much flatter than sticky price models with Calvo pricing or state-dependent pricing would imply.

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1 Introduction

A cornerstone implication of sticky price models is that when firms change their prices more often, aggregate demand fluctuations have a larger short-run effect on inflation. In other words, these models imply that the short-run Phillips curve is steeper when firms reprice more often.

In this paper, I test empirically whether the US Phillips curve slope depends positively on the frequency with which firms change their prices. I do so using a series for the frequency of price changes that Nakamura, Steinsson, Sun and Villar (2018) computed from price-level data.

I estimate Phillips curves which allow for the possibility that the slope depends linearly on the price adjustment frequency. I find a positive relation between the slope and the frequency. My findings suggest that the Phillips curve slope was flat at most times since the mid-1980s because price adjustment was relatively infrequent.

Second, I investigate the implication from standard New Keynesian theory with Calvo (1983) pricing that the Phillips curve slope is a convex function of the probability of price adjustment. This implication is embedded in the New Keynesian Phillips curve (NKPC).

To this end, I estimate Phillips curves with a slope that depends on the empirical frequency of price adjustment according to the same non-linear functional form as that of the NKPC. In line with New Keynesian theory with Calvo pricing, I find that the Phillips curve slope is an upward-sloping, convex function of the adjustment frequency.

Third, I quantify the level of the Phillips curve slope implied by sticky price models ranging from a pure Calvo model where there are no explicit costs of price adjustment to a pure state-dependent pricing model where all price adjustments require paying a menu cost. I do so by calibrating the NKPC such that it is consistent with the empirically observed values for the repricing rate in either of those models. For models featuring menu costs, I use the result from Auclert, Rigato, Rognlie and Straub (2023) that state-dependent pricing models with a particular (empirical) average frequency of price adjustment are observationally equivalent to a Calvo model with a particular, higher, frequency of price adjustment.

I find that at the repricing rates that were observed in the United States, all the tested theories with nominal rigidities imply a Phillips curve slope that is much steeper than the slope implied by my estimated Phillips curves. The Phillips curve slope implied by the Calvo model is on the order of ten times steeper than the empirical slope. State-dependent pricing models imply even steeper Phillips curves, with the gap increasing in the share of price adjustments that require a menu cost.

These findings suggest that a wide range of models with nominal rigidities substantially overstate the short-run response of inflation to aggregate demand fluctuations.

To my knowledge, this is the first paper to directly test whether the Phillips curve slope depends positively on the frequency of price adjustment.

Earlier papers provide indirect evidence. Ball, Mankiw and Romer (1988), DeFina (1991), De Veirman (2009) and Ball and Mazumder (2011) find that the Phillips curve slope depends positively on factors such as trend inflation and aggregate volatility. This is consistent with the implication of endogenous pricing models that higher trend inflation or a higher volatility of shocks causes firms to change their prices more frequently, which in turn causes the Phillips curve to steepen.[1] However, these studies do not examine whether it is indeed the frequency of price adjustment that affects the Phillips curve slope.[2] This is important because factors such as the volatility of shocks may affect the Phillips curve slope through mechanisms other than the frequency of price adjustment.[3] The present paper's test of whether the slope depends positively on the frequency is arguably a more direct test of sticky price models.

My finding that the Phillips curve was flat at most times since the mid-1980s relates to a large empirical literature that finds that the Phillips curve has flattened.[4] My results suggest a structural interpretation for such flattening, in that it appears to have been a consequence of declining repricing rates.

Beyond such a gradual flattening over the course of several decades, my results suggest that at times, fluctuations in the frequency imply fairly swift and large changes in the Phillips curve slope. For instance, I find that the Phillips curve was particularly steep around 1980, when firms changed their prices frequently, but flattened fairly quickly in the early 1980s when repricing rates dropped again. As for the Volcker disinflation, this suggests that the output

[1]See Costain, Nakov and Petit (2021) for the theoretical relation of the frequency of price adjustment to trend inflation and Vavra (2014) for its relation to firm-specific volatility. De Veirman and Schoenle (2023) test the latter implication empirically.

[2]Bils and Klenow (2004) and Nakamura and Steinsson (2008) provided comprehensive evidence on the frequency of price changes in the United States, for narrower time windows than in Nakamura e.a. (2018).

[3]See e.g. the Lucas (1973) misperceptions model and the rational inattention model of Maćkowiak and Wiederholt (2009).

[4]See, for instance, De Veirman (2009), Ball and Mazumder (2011), Blanchard, Cerutti and Summers (2015), Blanchard (2016), Del Negro, Lenza, Primiceri and Tambalotti (2020) and Okuda, Tsuruga and Zanetti (2023). On the other hand, Hazell, Herreño, Nakamura and Steinsson (2022) find using state-level data that the US Phillips curve has flattened only modestly since the early 1980s.

costs of a one percentage point decline in inflation were low initially, but increased as the disinflation progressed. Endogenous pricing models predict that this is a structural feature, in the sense that disinflations cause repricing rates to decline and therefore the Phillips curve to flatten.

My finding that the Phillips curve slope varies positively with repricing rates relates to the finding of Hong, Klepacz, Pasten and Schoenle (forthcoming) that monetary policy shocks have stronger effects on inflation in sectors where prices typically change more frequently. The approach in the present paper is different in that I estimate Phillips curves and gauge the implications of time-variation in repricing rates.

My finding that models with nominal rigidities substantially overstate the empirical Phillips curve slope is important given that sticky price models, and the Calvo model in particular, are in very common use as a basis for monetary policy advice. My finding relates to the notion that in order to produce realistic impulse responses, macro models with Calvo pricing commonly require unrealistically high values for the probability that prices are not adjusted.[5] The contribution of this paper is that I measure whether and to which extent sticky price models overstate the Phillips curve slope.

The remainder of the paper is organized as follows. Section 2 shows that empirically, the Phillips curve slope depends positively on the frequency of price changes. Section 3 documents that the relation between the slope and the frequency is convex both in the NKPC and in the data, but that the slopes implied by theories with nominal rigidities are much steeper than that of the empirical Phillips curve. Section 4 concludes.

[5] See a discussion on this point in Maćkowiak and Smets (2008).

2 Does the Phillips curve slope depend on the frequency of price adjustment?

In this section, I document that empirically, the Phillips curve slope depends positively on the frequency of price changes.

Figure 1 plots the data. The top panel shows the median frequency of consumer price adjustment in the United States from Nakamura, Steinsson, Sun and Villar (2018), with the blue line representing an unsmoothed quarterly series and the black line representing a backward-looking four-quarter moving average. Aiming to reduce the impact of any measurement error, I perform analysis with the smoothed series throughout this paper. Note that Nakamura e.a. (2018) focus on an annual series, plausibly for the same reason.

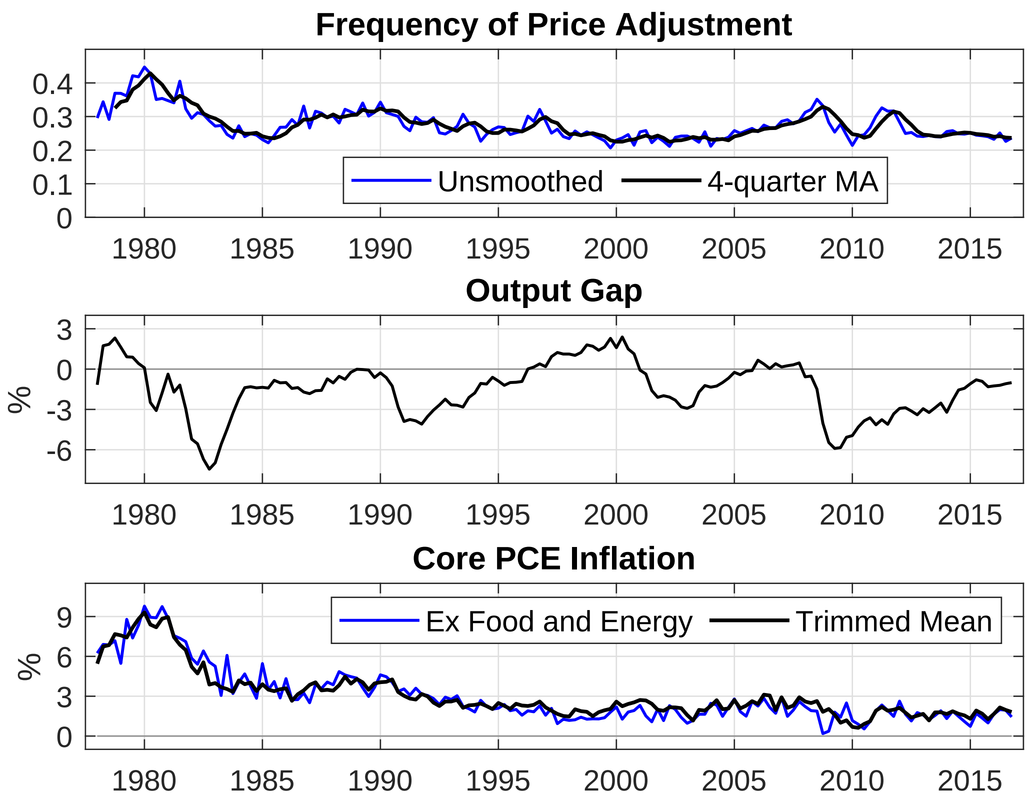
While Nakamura e.a. (2018) report the frequency as the fraction of prices that change per month, I express it as the fraction of price changes per quarter so as to allow for a comparison with the quarterly probability of price adjustment from sticky price models in Section 3.[6]

The middle panel of Figure 1 plots the output gap, which I computed as the percentage difference between real Gross Domestic Product (GDP) and Congressional Budget Office estimates of real potential output.

The bottom panel plots inflation in the deflator for Personal Consumption Expenditures

[6]Figure XIV in Nakamura, Steinsson, Sun and Villar (2018) plots an annual series for the frequency of price adjustment. I thank Jón Steinsson for sending me the underlying unsmoothed quarterly series $\widetilde{freq}_t^m$ expressed as the fraction of price changes per month. From this series, I first compute the frequency expressed as the fraction of price changes per quarter $\widetilde{freq}_t^q$ through the formula $(1-\widetilde{freq}_t^m)^3 = 1-\widetilde{freq}_t^q$. I then compute the four-quarter moving average as $freq_t = (1/4)\sum_{i=0}^{3}\widetilde{freq}_{t-i}^q$.

Figure 1. Data



The top panel plots the median frequency of US consumer price adjustment excluding sales, expressed as the share of prices that change per quarter. From the unsmoothed frequency (in blue), I computed the four-quarter backward-looking moving average (the thick black line). These series are based on data from Nakamura, Steinsson, Sun and Villar (2018). The middle panel plots the output gap, defined as the percent deviation of real Gross Domestic Product from the Congressional Budget Office estimate of real potential output. The bottom panel plots inflation in the deflator for Personal Consumption Expenditures ex food and energy (in blue) and trimmed mean PCE inflation from the Federal Reserve Bank of Dallas (the thick black line). Both cases pertain to annualized quarter-on-quarter inflation.

(PCE) excluding food and energy (in blue), as well as trimmed mean PCE inflation from the Federal Reserve Bank of Dallas (the thick black line). Trimmed mean PCE inflation is less volatile than PCE inflation ex food and energy. In particular, the former measure has smaller short-run fluctuations than the latter. Plausibly due to this feature, it turns out that my Phillips curve regressions for trimmed mean PCE inflation provide a better fit and tighter estimates than those with ex food and energy PCE inflation. As I discuss later in this section, this is why I use trimmed mean PCE inflation in the baseline.

Beyond these two measures for core PCE inflation, I report results using inflation in the constant methodology Bureau of Labor Statistics research series for the Consumer Price Index (CPI) excluding food and energy, and for inflation in the GDP deflator. Throughout, I use annualized quarter-on-quarter inflation.

Furthermore, I use three alternative ways of modelling inflation expectations. In the baseline, I use adaptive expectations. In a second case, I allow for a break in expectations formation as in Ball and Mazumder (2019). Third, I use survey expectations.

In this section, I specify the Phillips curve slope as a linear function of the frequency of price adjustment.

First consider the case with adaptive inflation expectations. With trimmed mean PCE inflation, I estimate the following regression:

$$\pi_t = \beta(L)\pi_t + (a + b\ freq_t)(ygap_t + \sum_{i=1}^{5} p_i\ ygap_{t-i}) + \varepsilon_t \tag{1}$$

where π_t is inflation, $freq_t$ is the frequency of price adjustment, $ygap_t$ is the output gap and ε_t is the residual. Equation (1) assumes adaptive inflation expectations. In particular, $\beta(L)\pi_t = \sum_{i=1}^{7} \beta_i \pi_{t-i}$. Furthermore, I impose $\beta_7 = (1 - \sum_{i=1}^{6} \beta_i)$, i.e., the inflation lag coefficients sum to one. This is equivalent to specifying the equation in terms of changes in inflation. I omit the intercept to avoid the possibility of a long-run trend in inflation. At the 5% level, Wald tests do not reject either of the latter two restrictions. In combination, these assumptions yield a Phillips curve where the expectations terms are those of a standard accelerationist Phillips curve.

The sample is 1978Q4-2016Q4, with earlier quarters used for lags. I selected the lag specification in equation (1) by means of the Akaike Information Criterion (AIC).

I measure the Phillips curve slope by the sum of the output gap coefficients. In equation (1), the sum of the output gap coefficients is $(a + b\ freq_t)(1 + \sum_{i=1}^{5} p_i)$. This specification allows the slope to vary over time due to changes in the frequency of price adjustment. Since the p's are time-invariant, it assumes that the coefficients on individual output gap terms remain in fixed proportions to one another.

First, I estimate a Phillips curve where I set $b = 0$, such that equation (1) reduces to a standard Phillips curve with a time-invariant slope.

The adjusted R-squared of the regression with trimmed mean PCE inflation is 0.95. A Breusch-Godfrey LM test for serial correlation up to eight lags reveals no serial correlation in the residuals.

The first row of the left numerical part of Table 1 reports results from a Wald test for the null hypothesis that $a(1 + \sum_{i=1}^{5} p_i) = 0$, which is the sum of the output gap coefficients after setting $b = 0$.

Throughout this paper, I use Newey-West heteroskedasticity and autocorrelation robust standard errors.

I find that the Phillips curve slope is 0.03 but statistically insignificant. Furthermore, this value is quite small in economic terms. In combination with the inflation lag coefficients, the Phillips curve slope implies that if the output gap is 1% for one year and 0 at all other times, annualized quarterly inflation increases by 0.11 percentage points in the long run.

Next, I allow the slope to depend on the frequency of price changes by estimating b along with the other coefficients. I perform Wald tests for the null hypothesis that $b(1+\sum_{i=1}^{5} p_i) = 0$, i.e. that the repricing rate has no effect on the sum of the output gap coefficients.

As the first numerical row of the right part of Table 1 shows, I find that $b(1+\sum_{i=1}^{5} p_i) = 1.92$, which is statistically significant at the 1% level. Since I express the price adjustment frequency as a variable ranging from 0 to 1, this means that a one percentage point increase in the frequency causes the Phillips curve slope to increase by a little less than 0.02.

The remainder of the upper left numerical part of Table 1 documents that with other inflation measures, the slope of the accelerationist Phillips curve is also positive. It is statistically significant at the 5% level with inflation in the PCE deflator ex food and energy. It is insignificant with inflation in the GDP deflator and in the constant methodology core CPI.

Note that among the four inflation measures, GDP deflator inflation is the only one that captures headline inflation. With GDP deflator inflation, I enter contemporaneous relative oil price inflation as a regressor.[7] This is equivalent to excluding oil price inflation from GDP

[7] In particular, I use relative inflation in the West Texas Intermediate spot crude oil price. In other respects, I keep the lag specification constant across inflation measures, i.e. I use seven inflation lags as well as the contemporaneous output gap and five of its lags, as selected by the AIC for trimmed mean inflation.

deflator inflation.

The corresponding rows in the right part of the table show that with inflation measures other than trimmed mean PCE inflation, I also find a positive relation between the Phillips curve slope and the frequency of price adjustment. The point estimates imply a somewhat stronger relationship than in the case of trimmed mean inflation. However, the standard errors are larger, and the relation is less significant statistically. With GDP deflator inflation, the relation is significant at the five percent level, but not so with ex food and energy inflation in the PCE deflator and in the CPI.

All in all, this constitutes evidence in favor of the hypothesis that the slope depends positively on the price adjustment frequency.

A plausible reason why the standard errors are smaller with trimmed mean inflation is that this inflation measure is arguably better at cleaning out transitory relative price shocks than ex food and energy measures of core inflation are. If trimmed mean inflation contains less noise, variation in this inflation measure would be more easily explained by the regressors in the Phillips curve. As such, one would expect the fit to be better. This is indeed what I find. In the accelerationist Phillips curve where the slope depends linearly on the frequency of price adjustment, the adjusted R-squared is 0.95 with trimmed mean inflation, as opposed to 0.88 for PCE inflation ex food and energy and somewhat lower still for the other inflation measures. The higher R-squared goes along with a smaller standard error of the regression, which tends to imply tighter confidence bands around the point estimates.[8]

[8] This interpretation is akin to that of Ball and Mazumder (2020) on the measurement of the Phillips curve slope with median inflation.

Table 1. Wald Tests: Phillips Curve Slope and Relation to Frequency of Price Adjustment

infexp	inflation	*Significant Phillips curve slope?* H_0: $a(1+\sum_{i=1}^{5} p_i) = 0$ slope	stderr	pval	*Significant relation to frequency?* H_0: $b(1+\sum_{i=1}^{5} p_i) = 0$ rel freq	stderr	pval
adaptive	PCE_TM	0.03	0.02	0.11	1.92**	0.62	0.00
adaptive	PCEX	0.07*	0.03	0.02	2.41	1.30	0.07
adaptive	GDPDEF	0.05	0.03	0.15	3.07*	1.22	0.01
adaptive	CPIX	0.06	0.04	0.13	2.51	1.43	0.08
Ball-Mazumder	PCE_TM	0.05**	0.02	0.00	1.52*	0.64	0.02
Ball-Mazumder	PCEX	0.10**	0.03	0.00	2.00	1.15	0.08
Ball-Mazumder	GDPDEF	0.05*	0.02	0.01	0.05	0.47	0.92
Ball-Mazumder	CPIX	0.20**	0.05	0.00	1.39	1.98	0.48
$\pi^e_{t\|t-1}$	GDPDEF	0.06	0.04	0.18	1.25	0.82	0.13
$\pi^e_{t+1\|t}$	GDPDEF	0.05	0.04	0.22	0.85	0.87	0.33
$\pi^e_{t+1\|t-1}$	GDPDEF	0.06	0.04	0.17	0.85	0.86	0.32

For Phillips curves with adaptive expectations as in equation (1), with Ball-Mazumder expectations as in equations (2) and (3) and with survey expectations as in equation (4), and with trimmed mean PCE inflation (PCE_TM), inflation in the PCE deflator ex food and energy (PCEX), GDP deflator inflation (GDPDEF) and inflation in the constant methodology research series for the CPI ex food and energy (CPIX), the left numerical part of this table reports on Wald tests for the hypothesis that the Phillips curve slope is zero while the right part reports on Wald tests for the hypothesis that the slope does not depend on the frequency of price changes. In each case, I report the value for the function of coefficients stated above the table, its standard error and the p-value of the F-statistic. For any τ_1 and τ_2, $\pi^e_{\tau_2|\tau_1}$ stands for Survey of Professional Forecasters forecasts formed in quarter τ_1 for inflation in τ_2. The sample is 1978Q4-2016Q4, with earlier quarters used for lags. For all inflation measures, lag specifications are as in equations (1) through (4) except for the fact that with GDP deflator inflation, I add contemporaneous relative oil price inflation as a regressor to equations (1) and (2). I use Newey-West standard errors. * marks significance at the 5% level; ** at the 1% level.

Adopting the interpretation that I can better pinpoint the relation with trimmed mean PCE inflation, in much of the paper I focus on results with trimmed mean PCE inflation.

For the case with trimmed mean PCE inflation, the blue line in Section 3's Figure 3 plots the time variation in the Phillips curve slope implied by the coefficient estimates for equation (1) and the empirical frequencies of price adjustment. I find that the Phillips curve slope varied between -0.06 in 2002Q2 and 0.33 in 1980Q2. Relative to the constant-coefficients slope of 0.03, that variation is substantial. (The interpretation of the other lines in this figure will become clear in Section 3.)

The implied changes in the Phillips curve slope are at times swift, a type of instability in the output-inflation trade-off which can greatly alter the effects of aggregate demand fluctuations.

A first example of this is the Volcker disinflation. The Phillips curve in which the slope depends linearly on the frequency implies that the slope was 0.33 in 1980Q2. Together with the inflation lag coefficients, this implies that if repricing rates would have stayed as high as in 1980Q2 and in the scenario that the output gap was -1% for a year and zero at all other times, that would have implied a long-run reduction in inflation by 1.16 percentage points. However, the frequency of price adjustment quickly declined from its 1980Q2 peak, such that on average in 1982, the implied Phillips curve slope was 0.13. With this slope, an output gap of -1% for one year implies a long-run reduction in inflation by 0.44 percentage points. This suggests that the output gap, which reached its trough at an average of -6.23 percent in 1982, had an effect on inflation that was less than half of what it would have been if the slope had stayed at its 1980Q2 level.

The Great Recession provides a second example of swift implied changes in the Phillips curve slope. The implied Phillips curve slope was 0.14 in 2008Q4. However, the slope declined swiftly after that, to essentially zero on average in 2010, where it stayed for most of the remainder of the sample period. This suggests that the output gap, which was -4.18% on average in 2010, had virtually no downward effect on inflation, as opposed to what would have occurred if the slope had stayed at 0.14. In the latter case, a -1% output gap for one year would have implied a long-run decline in inflation by 0.50 percentage points. This suggests that the negative output gaps in 2010 would have tended to imply a long-run decline in inflation by $4.18 * 0.50 = 2.09$ percentage points. Against the background that trimmed mean PCE inflation was 1.68% on average in 2008Q1-2016Q4, the implied differences in the effects of the output gap on inflation are substantial.

To further check robustness, I adopt an approach similar to that of Ball and Mazumder (2019) to account for the possibility that the process by which inflation expectations are formed has changed over time. With trimmed mean PCE inflation, I regress:

$$\begin{aligned}\pi_t = I(t \leq 1997)\ [\alpha_1 \pi^* + (1-\alpha_1)\gamma(L)\pi_t] + I(t \geq 1998)\ [\alpha_2 \pi^* + (1-\alpha_2)\gamma(L)\pi_t] \\ +(a + b\ freq_t)(ygap_t + \sum_{i=1}^{5} p_i\ ygap_{t-i}) + \varepsilon_t\end{aligned} \tag{2}$$

where $\pi^* = 2$ stands for the inflation target, $I(t \leq 1997)$ equals 1 through 1997Q4 and 0 otherwise while $I(t \geq 1998)$ is 1 from 1998Q1 onwards an 0 otherwise, and where:

$$\gamma(L) = \left(\frac{1-\gamma}{1-\gamma^7}\right)(\sum_{j=1}^{7} \gamma^{j-1}\pi_{t-j}) \tag{3}$$

In equation (3), the coefficients on the inflation lags decay geometrically and sum to one. Taken together, equations (2) and (3) imply that inflation expectations depend on a weighted average of the inflation target and lagged inflation, with the possibility of a structural break in the weights in 1998Q1. This is the break date identified by Ball and Mazumder (2019).[9]

The middle left numerical segment of Table 1 reveals that with Ball-Mazumder expectations, the slope is positive and statistically significant at the five percent level or better for every of the four inflation measures. The slope tends to be steeper than with adaptive expectations, a difference which is substantial in the case of core CPI inflation.

The middle right segment of the same table shows that with Ball-Mazumder expectations, the Phillips curve slope continues to depend positively on the frequency of price adjustment with trimmed mean PCE inflation as well as with ex food and energy inflation in the PCE deflator and in the CPI. In all these cases, the relationship is (somewhat) less strong than with adaptive expectations. With trimmed mean PCE inflation, the relation is significant at the five percent level. It is not with the two measures for ex food and energy inflation.[10]

[9]So as to be able to identify all coefficients of the Phillips curve that obtains after substituting (3) into (2), I select the regression with the highest $\bar{R}^2$ among all regressions with γ set to values ranging from 0.01 through 0.99. Throughout, I use the same lag lengths with Ball-Mazumder expectations as I do with adaptive expectations. For CPI inflation ex food and energy, I set $\pi^* = 2.5$. For the other three inflation measures, I set $\pi^* = 2$. This follows Ball and Mazumder's reasoning that while the Fed's inflation target is 2% in terms of the PCE deflator ex food and energy, this is consistent with a somewhat higher target value for core CPI inflation since core CPI inflation typically somewhat exceeds core PCE inflation.

[10]With trimmed mean PCE inflation, I find that $\alpha_1 = 0.00$ such that inflation expectations are estimated to be adaptive through 1997, while α_2 is 0.26 and statistically significant at the one percent level, indicating that inflation expectations were partially anchored to the target from 1998 onwards. In this same case, I find that the geometric decay parameter $\gamma = 0.22$.

While the above results on the relation between the slope and the frequency are quite similar to those with adaptive expectations, there is one clear difference: with GDP deflator inflation and Ball-Mazumder expectations, there is virtually no relation between the slope and the frequency.

In a final robustness check, I use survey expectations for inflation. In particular, I regress over 1978Q4-2016Q4:

$$\pi_t = \beta \pi^e_{t+1|t} + (a + b\ freq_t)\ ygap_t + \sum_{i=0}^{6} \gamma_i\ (\pi_{o,t-i} - \pi_{t-i}) + \varepsilon_t \tag{4}$$

where $\pi^e_{t+1|t}$ is the forecast from the Survey of Professional Forecasters (SPF) of GDP deflator inflation in quarter t+1, formed in quarter t. $\pi_{o,t} - \pi_t$ is relative inflation in the West Texas Intermediate spot crude oil price. As before, I selected lags based on the AIC.

An advantage of using survey expectations is that doing so can account for any type of structural change in the process by which inflation expectations are formed.

The SPF features one-quarter ahead forecasts. This is why I can include current expectations of next quarter's inflation, in which case the timing of expectations is the same as that of the New Keynesian Phillips Curve, which features in Section 3. Since the one-quarter ahead forecast is only available over the required time span for GDP deflator inflation, in this context I use GDP deflator inflation as the dependent variable.[11]

[11] The deadlines by which SPF forecasters need to submit their forecasts and the timing of the Bureau of Economic Analysis publications of the GDP deflator are such that when SPF forecasters make their forecast in quarter t, they know the preliminary estimate of the GDP deflator in $t-1$, but they do not know the GDP deflator in t. Against this background, equation (4) treats $\pi^e_{t+1|t}$ as exogenous.

The row marked $\pi^e_{t+1|t}$ in Table 1 summarizes the results. When I set $b = 0$ in equation (4), the point estimate for the Phillips curve slope is 0.05. This value is statistically insignificant.

When I estimate b along with the other coefficients in equation (4), I find that the Phillips curve slope depends positively on the frequency, but this relation is insignificant.

The rows $\pi^e_{t|t-1}$ and $\pi^e_{t+1|t-1}$ show that the results are similar when I instead use, respectively, SPF forecasts for quarter t formed in t-1 and forecasts for t+1 formed in t-1.[12]

Taken together, the results from this section suggest that the Phillips curve slope depends positively on the frequency of price adjustment, in line with sticky price models. The statistical significance of this relationship is only robust to allowing for structural change in expectations formation when I use trimmed mean inflation. This may be because trimmed mean inflation is good at filtering out noise and therefore yields precise estimates.

3 The Phillips curve slope: theory and empirics

In this section, I document that both in a standard New Keynesian model with Calvo pricing and in the data, the Phillips curve slope is a convex, increasing function of the repricing rate. I also show that at the repricing rates that occurred in the United States, the empirical Phillips curve slope is much flatter than the slopes implied by well-known sticky price models.

I first turn to theory, so as to set the stage for a comparison with the empirical estimates that I present later in this section. In sticky price models, the short-run Phillips curve is steeper when firms reprice more frequently. Perhaps the most widely used way to model sticky

[12]For each of the three specifications for survey expectations, I use the lag specification in equation (4), as selected by the AIC for the case with $\pi^e_{t+1|t}$.

prices in macro models is Calvo pricing. As Galí (2008) shows, a standard New Keynesian model with Calvo pricing implies the canonical New Keynesian Phillips Curve (NKPC):

$$\pi_t = \beta \; E_t \pi_{t+1} + \kappa \; ygap_t \tag{5}$$

In the above equation, inflation π_t depends on the contemporaneous output gap $ygap_t$ and on current rational expectations of future inflation $E_t \pi_{t+1}$. β is the household time discount factor. The coefficient on the output gap is:

$$\kappa \equiv \left(\frac{(1-\theta)(1-\theta\beta)}{\theta} \right) \left(\frac{1-\alpha}{1-\alpha+\alpha\epsilon} \right) \left(\frac{\phi+\alpha}{1-\alpha} + \sigma \right) \tag{6}$$

where θ is the probability that a firm cannot reset its price, $1-\alpha$ governs the marginal product of labor, ϵ governs the price elasticity of demand, ϕ governs the elasticity of labor supply and σ is the inverse of the household's intertemporal elasticity of substitution.

To examine what this implies for the level of the Phillips curve slope and for its relation to the adjustment probability, I now calibrate the structural parameters in (6) to standard values. In particular, I set $\beta = 0.9984$, $\alpha = 0.19$, $\phi = 1.83$ and $\sigma = 1.38$, all of which are full information estimates from Smets and Wouters (2007).[13] Furthermore, I set $\epsilon = 6$.

In Smets and Wouters (2007), all firms adjust prices every quarter, with a fraction of firms setting their prices optimally and a fraction indexing partially to inflation. Therefore, the Smets-Wouters model does not feature a parameter that could directly be compared to the empirical frequency of price adjustment.

[13] These values correspond to the mean of the posterior distribution in Smets and Wouters (2007).

In the model of Galí and Gertler (1999), a fraction of firms hold prices fixed every period, with some of the firms that do adjust doing so optimally and the remainder indexing fully to lagged inflation. Therefore, I consider the case where $\theta = 0.834$, which is Galí and Gertler's estimate for the probability that a price is not adjusted in their model.

I now plug the above values for the structural parameters into equation (6) to obtain the implied Phillips curve slope. Given that Smets and Wouters (2007) estimated their model on non-annualized quarterly data, I multiply the implied slope by four so as to allow for a comparison with the slopes from the empirical Phillips curves which I estimated with annualized quarterly inflation. I obtain $4\kappa = 0.21$. This is at the upper end of the range of the estimated Phillips curve slopes from Table 1 in Section 2.

With Galí and Gertler's (1999) estimated $\theta = 0.834$, price adjustment is less frequent than in the data from Nakamura e.a. (2018). On average in my sample, the empirical frequency of non-adjustment, expressed as a rate per quarter, is 0.7239. This illustrates the fact that typically, model-based estimates of the probability of price adjustment differ from empirical evidence on the adjustment frequency. When I instead set $\theta = 0.7239$, I obtain $4\kappa = 0.68$, which is not in the ballpark of my empirical estimates of the Phillips curve slope.

Therefore, with an empirically realistic value for the average frequency of non-adjustment and other structural parameters at standard values, the slope of the NKPC is much steeper than what I find in the data.[14]

[14] Note that even in the case with forward-looking survey expectations $\pi^e_{t+1|t}$, the specification required by the data is not entirely the same as that of the NKPC. This is for two reasons. First, as Coibion, Gorodnichenko and Kamdar (2018) discuss, empirical survey expectations typically do not conform to the assumption of rational expectations. Second, equation (4) controls for relative oil price inflation.

We are about to see that both the theoretical and empirical Phillips curve slopes are convex functions of the adjustment frequency. With convexity, Jensen's inequality implies in both the theoretical and the empirical case that the time average of the slopes implied by the empirical series of adjustment frequencies exceeds the slope evaluated at the average adjustment frequency. It is therefore important to evaluate the Phillips curve slope at a broader range of values for the frequency.

I do so now. The black curve in Figure 2 tracks the slope of the NKPC as a function of the probability of price adjustment, keeping other structural parameters at the above-mentioned values. The function is upward sloping, such that an increase in the adjustment probability implies a steeper Phillips curve. The function is convex, such that the slope varies more strongly with changes in repricing rates when many firms change their prices.

These are general features of the NKPC. To see this, first define the probability of price adjustment $\omega \equiv 1-\theta$ and rewrite equation (6) in terms of ω:

$$\kappa \equiv \left[(1-\beta)\left(\frac{\omega}{1-\omega}\right)+\beta\left(\frac{\omega^2}{1-\omega}\right)\right]\left(\frac{1-\alpha}{1-\alpha+\alpha\epsilon}\right)\left(\frac{\phi+\alpha}{1-\alpha}+\sigma\right) \tag{7}$$

Then take the first derivative of the slope of the NKPC as written in equation (7) with respect to the probability of price adjustment:

$$\frac{\delta\kappa}{\delta\omega}=\left(\frac{1-\beta(1-\omega)^2}{(1-\omega)^2}\right)\left(\frac{1-\alpha}{1-\alpha+\alpha\epsilon}\right)\left(\frac{\phi+\alpha}{1-\alpha}+\sigma\right) \tag{8}$$

By inspecting the sign of this derivative, we can see that the slope of the NKPC is increasing in the adjustment probability. If $0<\beta<1$ and $0<\theta<1$, then $1-\beta(1-\omega)^2>0$ and

$(1-\omega)^2 > 0$. If $0 \leq \alpha < 1$ and $\epsilon \geq 0$, then $1-\alpha > 0$ and $1-\alpha+\alpha\epsilon > 0$. If, in addition, $\phi \geq 0$ and $\sigma \geq 0$, then $[(\phi+\alpha)/(1-\alpha)]+\sigma \geq 0$. As a result, $\delta\kappa/\delta\omega \geq 0$.

Next, consider the second derivative of the slope of the NKPC with respect to the probability of price adjustment:

$$\frac{\delta^2\kappa}{\delta\omega^2} = \left(\frac{2}{(1-\omega)^3}\right)\left(\frac{1-\alpha}{1-\alpha+\alpha\epsilon}\right)\left(\frac{\phi+\alpha}{1-\alpha}+\sigma\right) \tag{9}$$

If $\theta > 0$, then $(1-\omega)^3 > 0$ and $\delta^2\kappa/\delta\omega^2 \geq 0$. That is to say, the slope of the NKPC is a convex function of the probability of price adjustment.

The blue line in Figure 2 charts the relation between the empirical Phillips curve slope from Section 2 and the frequency of price changes. As we found in Section 2, this relation is upward sloping. Recall that in that section, I imposed a linear relationship between the slope and the frequency.

In the United States in 1978Q4-2016Q4, the four-quarter moving average of the frequency of price adjustment ranged from 0.22 to 0.43 per quarter. Over this range, the empirical Phillips curve slope, specified as a linear function of the adjustment frequency, is always well below the slope implied by the New Keynesian model with Calvo pricing.

To see whether the assumption of a linear relation between the slope and the frequency in Section 2 accounts for these differences, I now estimate Phillips curves in which the slope depends on the frequency of price adjustment in a non-linear fashion akin to that of the NKPC. As before, I use trimmed mean PCE inflation in the baseline.

Notice in equation (7) that when one rewrites the slope of the NKPC in terms of the probability of price adjustment ω, the slope depends on two non-linear terms in this probability of adjustment: $[\omega/(1-\omega)]$ and $[\omega^2/(1-\omega)]$.

In one empirical specification, I write the Phillips curve slope as an unrestricted function of these two non-linear terms, after replacing the probability of price adjustment ω with the empirical frequency of price adjustment $freq_t$:

$$\pi_t = \beta(L)\pi_t + \left[c + d\ \left(\frac{freq_t}{1-freq_t}\right) + e\ \left(\frac{freq_t^2}{1-freq_t}\right)\right] (ygap_t + \sum_{i=1}^{5} p_i\ ygap_{t-i}) + \varepsilon_t \quad (10)$$

where $\beta(L)$ is as defined under equation (1). I call this the unrestricted non-linear specification.

In a second specification, I estimate:

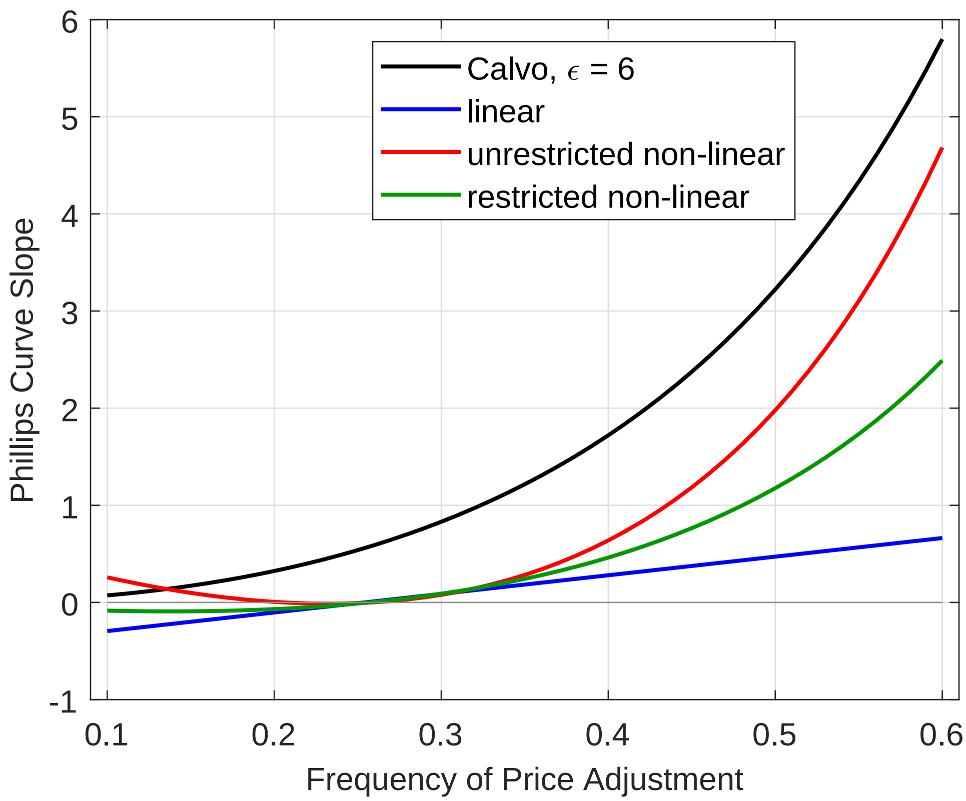
$$\pi_t = \beta(L)\pi_t + f\ \left[(1-g)\ \left(\frac{freq_t}{1-freq_t}\right) + g\ \left(\frac{freq_t^2}{1-freq_t}\right)\right] (ygap_t + \sum_{i=1}^{5} p_i\ ygap_{t-i}) + \varepsilon_t \quad (11)$$

I call this the restricted non-linear specification due to the fact that I restrict the coefficients on the two non-linear terms to sum to one like in equation (7). The parameter f stands for $[(1-\alpha)/(1-\alpha+\alpha\epsilon)][(\phi+\alpha)/(1-\alpha)+\sigma]$ from that equation.

In Figure 2, the red and green lines chart how the Phillips curve slope depends on the adjustment frequency in, respectively, the unrestricted and restricted non-linear case. In both cases, the function is upward-sloping and convex.[15] Recall that the empirical quarterly

[15]These results are with trimmed mean inflation and adaptive expectations. The finding is robust to using Ball-Mazumder expectations and to using ex food and energy inflation in the PCE deflator or in the CPI with either adaptive or Ball-Mazumder expectations. For all expectations measures, results with GDP

Figure 2. Phillips Curve Slope as a Function of the Frequency of Price Adjustment



The black line charts the slope of the New Keynesian Phillips Curve as a function of the quarterly probability of price adjustment as in equation (7), with other structural parameters at standard values, including $\epsilon = 6$. This is the theoretical slope with Calvo pricing. The colored lines indicate the relation between the empirical Phillips curve slope and the frequency of price adjustment in three cases. The blue, red and green lines pertain to the cases where the slope is, respectively, a linear, unrestricted non-linear, and restricted non-linear function of the frequency. The relevant equations are, respectively, (1), (10) and (11). In all cases, I use trimmed mean PCE inflation. Throughout, I express the slope such that it pertains to the response of inflation in annualized terms. In the US in 1978Q4-2016Q4, the adjustment frequency ranged from 0.22 to 0.43. In that range, all empirical slopes are well below the theoretical Phillips curve slope.

adjustment frequency ranges from 0.22 to 0.43 in my sample. For the higher adjustment frequencies within that range, the slopes from the non-linear specifications are closer to the theoretical slope than the slope that I specified as a linear function of the frequency. Among the three empirical specifications, the unrestricted non-linear specification is closest to theory.

Still, the empirical Phillips curve slope remains clearly below that of the slope of the New Keynesian Phillips curve at all observed values for the frequency of price adjustment.

To see this from another angle, Figure 3 shows the time path of theoretical and empirical Phillips curve slopes implied by the values for the frequency of price adjustment that occurred in the United States. In terms of models, I report the implications from both Calvo pricing and state-dependent pricing.

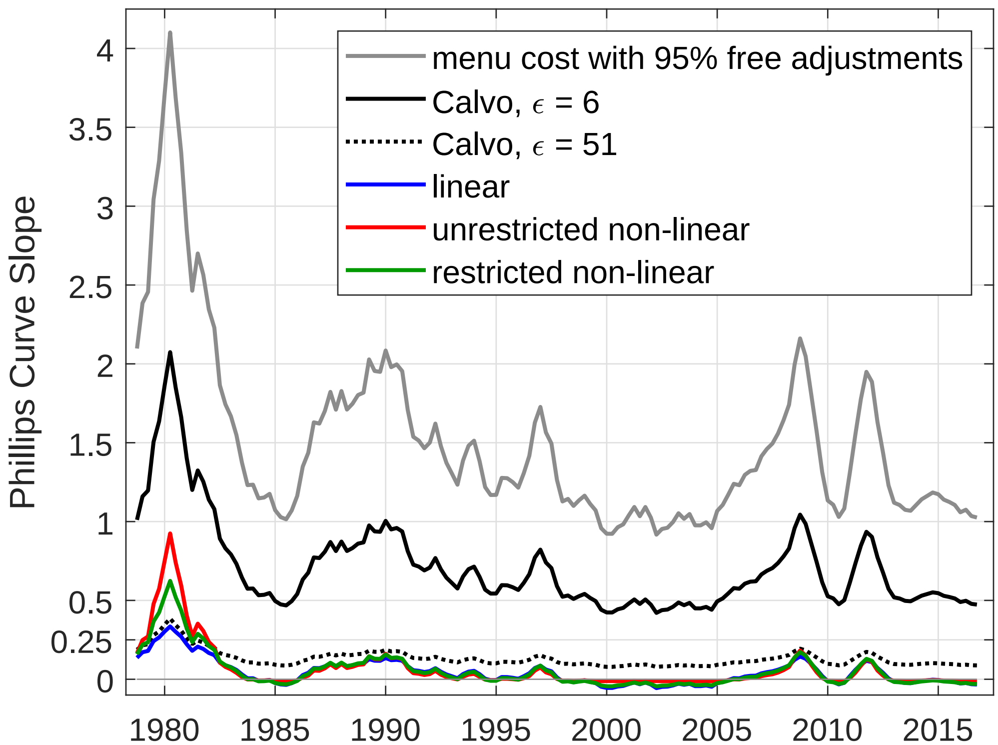
The solid black line in Figure 3 shows the path of the slope of the NKPC with Calvo pricing in the same case as that which I graphed in Figure 2, which includes $\epsilon = 6$.

For the unrestricted and restricted non-linear case, respectively, the red and green lines in Figure 3 show that relaxing the assumption of a linear relation bridges part of the gap between theory and empirics around 1980. At all other times, the differences between the linear and non-linear specifications are minor. In all cases in Figure 3, the empirical Phillips curve slope is always well below the theoretical slope.

Table 2 reports that with Calvo pricing and $\epsilon = 6$, the slope is 0.71 on average over the sample period. That table also reports that among the empirical specifications plotted in Figure 3, the average slope is steepest in the unrestricted non-linear case, at 0.07. Therefore,

deflator inflation are such that the relation is concave with the unrestricted non-linear specification and close to linear with the restricted non-linear function.

Figure 3. Phillips Curve Slopes Varying with the Empirical Frequency of Price Adjustment



This figure graphs theoretical and empirical Phillips curve slopes given the actual time path of the US frequency of price adjustment. The gray line charts the slope implied by a menu cost model with 95% free price adjustments, which I computed using the procedure in Auclert, Rigato, Rognlie and Straub (2023). The solid black line charts the slope of the New Keynesian Phillips Curve with Calvo pricing. In both of the foregoing cases, I set $\epsilon = 6$. The dotted black line charts the slope with Calvo pricing and $\epsilon = 51$. In all cases, I set other structural parameters at Smets and Wouters (2007) estimates. The colored lines pertain to empirical Phillips curve slopes. The blue, red and green lines represent the case where the slope is, respectively, a linear, unrestricted non-linear, and restricted non-linear function of the frequency. The relevant equations are, respectively, (1), (10), and (11). I use trimmed mean PCE inflation. Throughout, I express the slope such that it pertains to the response of inflation in annualized terms. At all times, all three empirical Phillips curve slopes are well below the model-implied slopes with the standard value of $\epsilon = 6$.

the theoretical slope is typically about ten times steeper than the slope in the unrestricted non-linear case.

Looking at particular episodes, the empirical Phillips curve slopes imply that the disinflation of the early 1980s was much costlier than theory with Calvo pricing implies.

At the end of the sample, the empirical slopes imply that to the extent that expansionary monetary policy was able to shift the aggregate demand curve to the right, this would have stimulated real output to a substantial extent while it would have had small short-run effects on inflation. To be sure, the Phillips curve is only one part of the picture. The effect of monetary policy stimulus on aggregate demand depends on other factors, such as whether monetary policy is at the effective lower bound on nominal interest rates and on the extent to which monetary policy transmission through the banking system is operative.

In another effort to explain the discrepancy between theory and empirics, I alter the price elasticity of demand. In the New Keynesian model with Calvo pricing, a re-optimizing firm raises its price when it observes an increase in the demand for its product. At the same time, the firm takes into account that this price rise tends to dampen the increase in demand, which in turn dampens the optimal size of the price increase. With a high price elasticity of demand ϵ, this dampening effect is large, such that the overall effect of the initial increase in demand on the optimal price is small. This implies that inflation does not increase as much in response to an increase in aggregate demand. In sum, an increase in the elasticity of demand tends to imply a flatter Phillips curve.

The black dotted line in Figure 3 represents the NKPC slope when I set $\epsilon = 51$, implying a very high degree of competition and therefore very elastic demand, while keeping the other structural parameters unchanged.

The increase in the elasticity of demand does imply a substantially flatter Phillips curve. In the first three years of the sample, the empirical slopes specified as a non-linear function of the frequency actually exceed the slope of the NKPC with $\epsilon = 51$. At all later times, the theoretical slope still exceeds the empirical ones.

Table 2 reports that the slope with Calvo pricing and $\epsilon = 51$ is 0.13 on average. Therefore, by imposing a value for the elasticity of substitution that far exceeds the range of typical values, most of the discrepancy disappears. Arguably, this value for ϵ is implausible, such that this finding can hardly be seen as an explanation for the gap between theory and empirics.

With all four inflation measures and with any of the three types of expectations, the empirical Phillips curve slopes remain substantially below the slope of the NKPC at baseline parameters.

So far, I have focused on the Calvo model of price setting. With Calvo pricing, the probability of non-adjustment is a structural parameter. In such a context, agents expect that the probability of price adjustment remains constant. This is hard to reconcile with the observation from Figure 1 that in the data, the frequency of price adjustment varies substantially over time.

It is therefore instructive to gauge what state-dependent pricing models imply for the slope of the Phillips curve. State-dependent pricing models stand a much better chance at explaining the observed short-run fluctuations in the adjustment frequency in that they imply that the frequency of price adjustment varies endogenously.

A challenge in gauging the Phillips curve slope in state-dependent pricing models is that

Table 2. Average Phillips Curve Slope: Models vs. Empirical Phillips Curves

		Share free adjustments	ϵ	Average slope
Models	Golosov-Lucas	0	6	10.54
	CalvoPlus	75	6	3.38
	CalvoPlus	90	6	2.01
	CalvoPlus	95	6	1.50
	Calvo	100	6	0.71
	Calvo	100	51	0.13
Empirical Phillips curves	Unrestr. non-linear	-	-	0.07
	Restr. non-linear	-	-	0.05
	Linear	-	-	0.04

The rightmost column reports the time-average of the Phillips curve slopes implied by the empirical frequencies of price adjustment in 1978Q4-2016Q4 for sticky price models as well as for the Phillips curves that I estimate. I use the procedure of Auclert e.a. (2023) to compute the Phillips curve slopes implied by a pure state-dependent pricing model as in Golosov and Lucas (2007) and by CalvoPlus models in which some price changes incur a menu cost while others are free. As for empirical Phillips curves, I tabulate results with trimmed mean PCE inflation in which the Phillips curve slope is, from top to bottom, an unrestricted non-linear, restricted non-linear, and linear function of the frequency of price adjustment. The relevant equations are, respectively, (10), (11) and (1). For the models, the leftmost numerical column indicates the percentage share of price adjustments for which firms do not incur a menu cost while the column labeled ϵ states the parameter governing the price elasticity of demand. Throughout, I express the slope such that it pertains to the response of inflation in annualized terms.

these models typically do not feature an expression for the Phillips curve.[16] However, a new paper by Auclert, Rigato, Rognlie and Straub (2023) shows that in general, a state-dependent pricing model with a particular average frequency of price adjustment is observationally equivalent to a Calvo model with a higher value for the probability of price adjustment.[17]

The reason for this is as follows. In the Calvo model, firms do not pay a menu cost when they change their price, whereas in state-dependent pricing models, at least some price adjustments require a menu cost. When a firm faces such a cost of price adjustment, it will only carry out a price change if the benefit of price adjustment is sufficiently large. Therefore, unlike the Calvo model, state-dependent pricing models feature a "selection effect" whereby firms that adjust their prices tend to be those that desire larger price changes. At any frequency of price adjustment, the selection effect towards larger price changes implies that inflation responds more strongly to aggregate demand fluctuations in state-dependent pricing models than in the Calvo model. The findings of Auclert e.a. (2023) imply that by setting the probability of price adjustment to a higher value in the Calvo model, one can compensate for the absence of a selection effect in that model and generate essentially the same response of any macroeconomic variable to any shock as in a state-dependent pricing model.

Auclert e.a. (2023) consider a range of state-dependent pricing models. These include a pure state-dependent pricing model where all price adjustments incur a menu cost as in

[16] Bakhshi, Khan and Rudolf (2007) and Gertler and Leahy (2008) derive Phillips curves for specific state-dependent pricing models.

[17] Costain, Nakov and Petit (2021) report that to minimize the distance in terms of the dynamic responses of output and inflation to monetary shocks between a Calvo model and their model with state-dependent price and wage setting, the Calvo model requires a higher-than-empirical probability of price adjustment.

Golosov and Lucas (2007). These also include various shades of the "CalvoPlus" model, where some price adjustments are free as in the Calvo model but where others are subject to a menu cost. The CalvoPlus model of Auclert e.a. (2023) is a one-sector variant of one of the models in Nakamura and Steinsson (2010). The larger the share of price adjustments that is subject to a menu cost, the stronger the selection effect, and the higher the probability of price adjustment that one has to feed into the Calvo model in order to make it observationally equivalent to that particular state-dependent pricing model.[18]

I implement the procedure of Auclert e.a. (2023) to compute the Phillips curve slope at the observed frequencies of price adjustment for a range of state-dependent pricing models.

I start by translating every observed value for the moving average of the frequency of price adjustment in 1978Q4-2016Q4 to the implied price duration. Next, I use the mapping from Auclert e.a. (2023) to translate these empirical price durations into the price durations that one needs to feed into the Calvo model in order to achieve observational equivalence with a range of state-dependent pricing models. I compute $dur_t^C = \alpha \; dur_t$, where dur_t is the empirical price duration, α is the proportionality factor from Auclert e.a. (2023), and dur_t^C is the duration that one needs to feed into the Calvo model in order to achieve equivalence with a state-dependent pricing model. As long as some price adjustments involve a menu cost, $\alpha < 1$. The higher the share of costly price adjustments, the smaller α.

Next, I translate the durations dur_t^C into frequencies of price adjustment. These are the adjustment frequencies that one needs to feed into the Calvo model to achieve equivalence

[18]Costain and Nakov (2011) show that a higher degree of state dependence implies a stronger selection effect.

to a number of state-dependent pricing models.[19] Finally, I feed these series of frequencies into the New Keynesian Phillips Curve slope κ from equation (6), with $\epsilon = 6$ and all other structural parameters at their Smets-Wouters (2007) estimates. As before, I report 4κ so as to express the slope in terms of the effect on annualized inflation.

The gray line in Figure 3 shows the Phillips curve slope at the observed frequencies of price adjustment in a model where 95% of price adjustments are free while 5% of price adjustments incur a menu cost. Having 5% of costly price changes substantially raises the Phillips curve slope. As Table 2 shows, the average Phillips curve slope in my sample period is 1.50. This is over two times as steep as in a pure Calvo model.

Table 2 reports the average Phillips curve slope for a wider range of state-dependent pricing models. The case with 75% free adjustments, which is the case which Auclert e.a. (2023) prefer for their CalvoPlus model, implies an average Phillips curve slope of 3.38. The case with 0% free adjustments, which corresponds to the Golosov-Lucas (2007) state-dependent pricing model, implies an average Phillips curve slope of 10.54.

Therefore, state-dependent pricing models overstate the empirical Phillips curve slope by even more than the Calvo model does. I find that this difference between state-dependent and Calvo pricing is quantitatively important. State-dependent pricing models provide increased realism at the micro level in that they account for the fact that firms choose when they

[19] I use the formula $dur_t = (1/freq_t) - 1$ from Auclert e.a. (2023) to translate frequencies $freq_t$ to durations dur_t and back. I thank Ludwig Straub for sending me the α's underlying Figure 9 in Auclert, Rigato, Rognlie and Straub (2023) by means of which I translated empirical price durations to those which one needs to assume in the Calvo model to achieve observational equivalence with various state-dependent pricing models.

adjust their prices, but my results suggest that this comes at the cost of a substantially larger departure from the empirical macroeconomic relation between output and inflation.

Taken together, my results suggest that a broad range of models with nominal rigidities overstate the short-run response of inflation to aggregate demand fluctuations.

4 Conclusion

Consistent with sticky price models, I find that the slope of the Phillips curve depends positively on the frequency of price changes. Consistent with theory with Calvo pricing, I find that the slope is a convex function of the repricing rate. My results suggest that the empirical Phillips curve is much flatter than sticky price theories would imply. This difference between empirics and theory applies to Calvo pricing as well as to state-dependent pricing, but is increasing in the share of price adjustments which is state dependent.

The positive relation between the Phillips curve slope and the repricing rate suggests that over the past several decades, a trend decline in repricing rates caused the Phillips curve to flatten. Matters may be different nowadays: Montag and Villar (2022) find that in the United States, the frequency of consumer price adjustment has doubled from early 2020 to early 2022.[20] This suggests that the Phillips curve is currently steep. This may explain why Cerrato and Gitti (2023) find, in US regional panel data, that the Phillips curve has recently steepened.

This suggests that the current situation bears similarities to that of the early 1980s, for which I find that the Phillips curve was steep as a result of high repricing rates, which in

[20] Dedola e.a. (2023) similarly report a large increase in repricing rates in France from 2021 onwards.

turn were plausibly caused by high inflation and volatile energy prices. A steep Phillips curve would imply that the costs of disinflation are currently lower than they typically are.

My findings on the gap between theory and empirics imply that when calibrated to micro evidence on the frequency of price adjustment, a broad class of models with nominal rigidities imply substantially steeper output-inflation trade-offs than what is the case in the data.

Real rigidities constitute a promising line of research to reduce this gap between theory and empirics. When combined with nominal rigidities, real rigidities can imply that firms, when re-optimizing their prices after a shock, carry out smaller price changes because they take into account the stickiness in the reaction of the prices of their competitors or suppliers. Real rigidities tend to flatten the Phillips curve relative to models where only nominal rigidities are present.

An important area of research is therefore to assess whether the strength of real rigidities that are present in the data is sufficient to match empirical output-inflation co-movement, and to investigate the relative importance of various potential sources of real rigidities.[21] In this context, one should arguably focus on the discrepancy in the Phillips curve slope between the data and state-dependent pricing models, since these models are more realistic

[21] Dedola, Kristoffersen and Züllig (2023) and Dedola e.a. (2023) find that real rigidities are empirically relevant in that prices which adjust in response to supply and demand shocks typically do so by small amounts initially. Real rigidities can give rise to strategic complementarities in price setting, in the sense that the level to which re-optimizing firms set their price depends positively on prices of other firms. Carvalho, Dam and Lee (2020) find evidence for strong strategic complementarities in the sense of the seminal model of Ball and Romer (1990). Madeira (2014) constructs a model with flexible overtime work but with real rigidities in the form of adjustment costs to straight-time work. Input-output linkages among firms are another potential source of real rigidities. For models with such linkages, see Smets, Tielens and van Hove (2018), Höynck (2023), Pasten, Schoenle and Weber (forthcoming) and Rubbo (forthcoming).

in the sense that they account for the fact that firms choose when they adjust their prices. Since the discrepancy is larger for state-dependent pricing models, these models may require a larger influence of real rigidities for them to become consistent with the empirical Phillips curve slope.[22]

Another candidate explanation for the gap between theory and empirics lies in the challenges in Phillips curve estimation stemming from the response of monetary policy to inflation, as detailed by McLeay and Tenreyro (2019). If Phillips curve slopes estimated using standard ways were to be downward biased, this could explain some of the discrepancy. De Veirman and Nakov (2023) examine whether (and under which conditions) conventional ways of identifying the Phillips curve slope yield biased estimates.

[22] As a factor other than real rigidities, Carvalho (2006), Nakamura and Steinsson (2010) and Gautier and Le Bihan (2022) show that cross-sector heterogeneity in price stickiness causes monetary policy to have larger real effects and more sluggish effects on inflation. Carvalho (2006) explains that such increased sluggishness in inflation partly springs from an extra term in the Phillips curve capturing the effect of other sectors' output gaps, whereas the effect of heterogeneity on the Phillips curve slope is ambiguous.

References

[1] Auclert, Adrien, Rodolfo Rigato, Matthew Rognlie, and Ludwig Straub, "New Pricing Models, Same Old Phillips Curve?" Harvard University mimeograph (2023).

[2] Bakhshi, Hasan, Hashmat Khan, and Barbara Rudolf, "The Phillips Curve under State-Dependent Pricing," *Journal of Monetary Economics* 54:8 (2007), 2321-2345.

[3] Ball, Laurence, N. Gregory Mankiw, and David Romer, "The New Keynesian Economics and the Output-Inflation Trade-Off," *Brookings Papers on Economic Activity* 1988:1 (1988), 1-82.

[4] Ball, Laurence, and Sandeep Mazumder, "Inflation Dynamics and the Great Recession," *Brookings Papers on Economic Activity* 2011:1 (2011), 337-381.

[5] Ball, Laurence, and Sandeep Mazumder, "The Nonpuzzling Behavior of Median Inflation," in Gonzalo Castex, Jordi Galí and Diego Saravia (eds.), *Changing Inflation Dynamics, Evolving Monetary Policy* (Santiago, Chile: Banco Central de Chile, 2020), 49-70.

[6] Ball, Laurence, and Sandeep Mazumder, "A Phillips Curve with Anchored Expectations and Short-Term Unemployment," *Journal of Money, Credit and Banking* 51:1 (2019), 111-137.

[7] Ball, Laurence, and David Romer, "Real Rigidities and the Non-Neutrality of Money," *Review of Economic Studies* 57:2 (1990), 183-203.

[8] Bils, Mark, and Peter J. Klenow, "Some Evidence on the Importance of Sticky Prices," *Journal of Political Economy* 112:5 (2004), 947-985.

[9] Blanchard, Olivier, "The Phillips Curve: Back to the '60s?" *American Economic Review: Papers and Proceedings* 106:5 (2016), 31-34.

[10] Blanchard, Olivier, Eugenio Cerutti, and Lawrence Summers, "Inflation and Activity - Two Explorations and Their Monetary Policy Implications," *European Central Bank Forum on Central Banking: Conference Proceedings* (2015), 25-46.

[11] Calvo, Guillermo A, "Staggered Contracts in a Utility-Maximizing Framework," *Journal of Monetary Economics* 12:3 (1983), 383-398.

[12] Carvalho, Carlos, "Heterogeneity in Price Stickiness and the Real Effects of Monetary Shocks," *Frontiers in Macroeconomics* 2:1 (2006).

[13] Carvalho, Carlos, Niels Arne Dam, and Jae Won Lee, "The Cross-Sectional Distribution of Price Stickiness Implied by Aggregate Data," *Review of Economics and Statistics* 102:1 (2020), 162-179.

[14] Cerrato, Andrea, and Giulia Gitti, "Inflation Since Covid: Demand or Supply," Brown University mimeograph (2023).

[15] Coibion, Olivier, Yuriy Gorodnichenko, and Rupal Kamdar, "The Formation of Expectations, Inflation, and the Phillips Curve," *Journal of Economic Literature* 56:4 (2018), 1447-1491.

[16] Costain, James, and Anton Nakov, "Price Adjustments in a General Model of State-Dependent Pricing," *Journal of Money, Credit and Banking* 43:2-3 (2011), 385-406.

[17] Costain, James, Anton Nakov, and Borja Petit, "Flattening of the Phillips Curve with State-Dependent Prices and Wages," *Economic Journal* 132:642 (2021), 1-36.

[18] De Veirman, Emmanuel, "What Makes the Output-Inflation Trade-Off Change? The Absence of Accelerating Deflation in Japan," *Journal of Money, Credit and Banking* 41:6 (2009), 1117-1140.

[19] De Veirman, Emmanuel and Anton Nakov, "Estimating the Slope of the Phillips Curve," European Central Bank and De Nederlandsche Bank mimeograph (2023).

[20] De Veirman, Emmanuel and Raphael Schoenle, "Idiosyncratic Volatility and Pricing Decisions," Brandeis University and De Nederlandsche Bank mimeograph (2023).

[21] Dedola, Luca, Erwan Gautier, Anton Nakov, Sergio Santoro, Emmanuel De Veirman, Lukas Henkel, and Bruno Fagandini, "Some Implications of Micro Price Setting Evidence for Inflation Dynamics and Monetary Transmission," European Central Bank Occasional Paper 321 (2023).

[22] Dedola, Luca, Mark Strøm Kristoffersen and Gabriel Züllig, "The Extensive and Intensive Margin of Price Adjustment to Cost Shocks: Evidence from Danish Multiproduct Firms," European Central Bank mimeograph (2023).

[23] DeFina, Robert H, "International Evidence on a New Keynesian Theory of the Output-Inflation Trade-off," *Journal of Money, Credit and Banking* 23:3 (1991), 410-422.

[24] Del Negro, Marco, Michele Lenza, Giorgio E. Primiceri, and Andrea Tambalotti, "What's Up with the Phillips Curve?" *Brookings Papers on Economic Activity* 2020:1 (2020), 301-373.

[25] Galí, Jordi, *Monetary Policy, Inflation, and the Business Cycle. An Introduction to the New Keynesian Framework* (Princeton, NJ: Princeton University Press, 2008).

[26] Galí, Jordi and Mark Gertler, "Inflation Dynamics: a Structural Econometric Analysis". *Journal of Monetary Economics* 44:2 (1999), 195-222.

[27] Gautier, Erwan and Hervé Le Bihan, "Shocks versus Menu Costs: Patterns of Price Rigidity in an Estimated Multisector Menu-Cost Model," *Review of Economics and Statistics* 104:4 (2022), 668-685.

[28] Gertler, Mark, and John Leahy, "A Phillips Curve with an Ss Foundation," *Journal of Political Economy* 116:3 (2008), 533-572.

[29] Golosov, Mikhail, and Robert E. Lucas, "Menu Costs and Phillips Curves," *Journal of Political Economy* 115:2 (2007), 171-199.

[30] Hazell, Jonathon, Juan Herreño, Emi Nakamura, and Jón Steinsson, "The Slope of the Phillips Curve: Evidence from U.S. States," *Quarterly Journal of Economics* 137:3 (2022), 1299-1344.

[31] Hong, Gee Hee, Matthew Klepacz, Ernesto Pasten, and Raphael Schoenle, "The Real Effects of Monetary Shocks: Evidence from Micro Pricing Moments," *Journal of Monetary Economics* (forthcoming).

[32] Höynck, Christian, "Production Networks and the Flattening of the Phillips Curve," Banco d'Italia mimeograph (2023).

[33] Lucas, Robert E., "Some International Evidence on Output-Inflation Tradeoffs," *American Economic Review* 63:3 (1973), 326-334.

[34] Maćkowiak, Bartosz, and Frank Smets, "On Implications of Micro Price Data for Macro Models," European Central Bank Working Paper 960 (2008).

[35] Maćkowiak, Bartosz, and Mirko Wiederholt, "Optimal Sticky Prices under Rational Inattention," *American Economic Review* 99:3 (2009), 769-803.

[36] Madeira, João, "Overtime Labor, Employment Frictions, and the New Keynesian Phillips Curve," *Review of Economics and Statistics* 96:4 (2014), 767-778.

[37] McLeay, Michael and Silvana Tenreyro, "Optimal Inflation and the Identification of the Phillips Curve," *NBER Macroeconomics Annual* 34 (2019), 199-255.

[38] Montag, Hugh, and Daniel Villar, "Price-Setting During the Covid Era," Bureau of Labor Statistics Working Paper 547 (2022).

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

[40] Nakamura, Emi, and Jón Steinsson, "Monetary Non-Neutrality in a Multisector Menu Cost Model," *Quarterly Journal of Economics* 125:3 (2010), 961-1013.

[41] Nakamura, Emi, Jón Steinsson, Patrick Sun, and Daniel Villar, "The Elusive Costs

of Inflation: Price Dispersion During the U.S. Great Inflation," *Quarterly Journal of Economics* 133:4 (2018), 1933-1980.

[42] Okuda, Tatsushi, Tomohiro Tsuruga, and Francesco Zanetti, "Imperfect Information, Heterogeneous Demand Shocks, and Inflation Dynamics," University of Oxford mimeograph (2023).

[43] Pasten, Ernesto, Raphael Schoenle and Michael Weber, "Real Rigidity and the Granular Origins of Aggregate Fluctuations," *American Economic Journal: Macroeconomics* (forthcoming).

[44] Rubbo, Elisa, "Networks, Phillips Curves, and Monetary Policy," *Econometrica* (forthcoming).

[45] Smets, Frank, Joris Tielens, and Jan van Hove, "Pipeline Pressures and Sectoral Inflation Dynamics," National Bank of Belgium Working Paper 351 (2018).

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

[47] Vavra, Joseph, "Inflation Dynamics and Time-Varying Volatility: New Evidence and an Ss Interpretation," *Quarterly Journal of Economics* 129:1 (2014), 215-258.