Do Sticky Prices Need to Be Replaced with Sticky Information?*

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Abstract

A first generation of research found it difficult to reconcile observed inflation and cyclical output with the sticky price mechanism. Since then, researchers have been divided roughly into two camps. The first camp argues that the original mechanism is largely successful once some backward-looking firms are permitted, i.e., the hybrid New Keynesian model, and cyclical output is replaced with labor's share. The second camp argues for a wholesale replacement of sticky prices, e.g., with 'sticky information' firms. We take up the question by estimating each camp's preferred model, along with a model that integrates sticky prices and information, which we call dual stickiness. In terms of goodness of fit and implied model dynamics, the hybrid model performs better than and comparably to the sticky information and dual stickiness models, respectively. Notably, the second camp's strongest merit can be drawn from a well-known significant influence of backward-looking behavior on inflation in the hybrid model. As such, our dual stickiness model (with our estimates of only seven month average information delays) may provide more plausible microeconomic foundations than the hybrid model.

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1 Introduction

The interaction of real activity and inflation is a cornerstone issue of macroeconomics. As with every major macro question, it has been placed under the lens of rational expectations and micro-founded dynamics in recent decades. Approximately fifteen years ago, efforts to estimate then existing models of price rigidity intensified.[1] These efforts center on the aggregated Euler equation from a rational expectations sticky price model, often called the New Keynesian Philips Curve (NKPC). A number of authors have argued that the NKPC is empirically deficient. Fuhrer and Moore (1995) find that inflation is more persistent than the models imply. Mankiw (2001, pg. C59) pointed out that the NKPC "is not at all consistent with the standard stylized facts about the dynamic effects of monetary policy, according to which monetary shocks have a delayed and gradual effect on inflation". Broadly speaking, experts have fallen into one of two camps on the NKPC's empirical adequacy.

The first group contends that only minor adjustments are needed. Gali and Gertler (1999) and Sbordone (2002) state that accurate measures of price dynamics require accurate measures of firms' marginal costs. They show that the NKPC fares much better if marginal cost is measured by labor share and also present reasonable assumptions that justify the measure theoretically. With the above correction, Gali and Gertler further find that sticky prices combined with a small fraction of backward looking firms match U.S and European data very well.

The second group advocates a major overhaul of the NKPC. A few of the alternatives include imperfect common knowledge (Woodford 2002) and sticky information (Mankiw and Reis 2002, Reis 2005). This group resuscitates the Fischer's (1977) wage-contract model by applying it to final good price setting. In Fischer's model, workers and firms negotiate wage contracts infrequently. Over a contract's life, wages may change; however, they cannot evolve according to newly available information.

[1] The existing models at that time included Calvo (1983), Rotemberg (1982) and Taylor (1980).

In Mankiw and Reis, on the other hand, firms choose future price plans infrequently, based on currently available information. They further modify Fischer's model by assuming plans have random rather than fixed durations and motivate the behavior through firm inattentiveness. Calibrations of their sticky price economy: (i) match the persistence of inflation; (ii) imply costly disinflations; and (iii) generate hump shaped responses of inflation and output to monetary shocks. For these reasons, they propose to replace the sticky price model with sticky information.

Given the above discussion, logical questions are: How does the data view the second group's proposal to replace the sticky price model with sticky information? Alternatively, should sticky price models be abandoned? If not, should sticky information be then abandoned? Our paper integrates these two groups' alterations in a nested structural analysis. Following a key concern of the first group, we measure marginal cost using labor share.

We also present an original model where each firm has two adjustment probabilities every period: a chance to reset its price and an independently distributed chance to update its information. Among firms that reset their prices, a fraction of firms choose its nominal price with new information and the remaining determines the price with stale information. It can be done by replacing backward-looking firms with inattentive firms which have old information but otherwise set their price optimally. We estimate the model using post-WWII U.S. data and compare our "dual stickiness model" to its alternatives.

Our findings are summarized as follows. First, our results contravene a wholesale replacement of sticky price with sticky information in terms of goodness-of-fit. Therefore, sticky price models need not be abandoned. Second, the dual stickiness model performs as well as the hybrid model in terms of goodness-of-fit. As such, the dual stickiness model may provide a more plausible microeconomic foundation: Thus sticky information need not be abandoned either. Third, in our benchmark estimation, each period a 15 percent of firms reset a price and a 39 percent of the firms are attentive. As a consequence, only 5.8 percent of firms in the economy choose the optimizing price each period. Finally, we measure the relative importance of each stickiness and find that sticky prices are more important than sticky information in accounting for inflation dynamics. All of our findings suggest that sticky prices play a more pivotal role than sticky information in explaining inflation dynamics.

Our paper does not address a more recent debate on the importance of future real marginal cost in explaining current inflation. This recent debate centers on the appropriate metric to evaluate the hybrid model. First, Gali and Gertler (1999), Gali, Gertler and López-Salido (2005) and Sbordone's (2005) endorsement of the model is based on estimates that a majority of firms are forward-looking in a structural model that also allows for backward-looking firms. Second, criticism by Ruud and Whelan (2005a, 2005b, 2006) stems from their finding that, in a reduced form model, there is no statistically significant relationship between future real marginal cost and inflation. Our paper restricts attention to the structural estimates of the hybrid, dual stickiness and sticky information models. Thus, it is closer to the former metric. In ongoing research, we are assessing the various models using Rudd and Whelan's approach.

Two existing papers also estimate models with both sticky information and prices: Korenok (2005) and Rotemberg and Woodford (1997). While instructive, neither answers the questions we propose. The former tests the relative importance of the two components via encompassing tests, suggesting that the sticky prices dominate sticky information. The latter uses an estimation strategy that cannot separately identify the amount of each stickiness. Only the former uses labor share–an essential adjustment required by the first group–to measure marginal cost. We present an expanded discussion of related research in Section 4.

An outline of the rest of the paper follows. Section 2 describes the sticky information and sticky price model. Section 3 presents our empirical findings. Section 4 compares each inflation equation in general equilibrium. Section 5 discusses existing research contextually. The final section concludes.

2 The Two Pricing Problems

2.1 The hybrid sticky price model

Consider a continuum of firms engaged in monopolistic competition. Suppose that each firm is ex ante identical and faces infrequent price setting. Each firm has the probability $(1-\gamma)$

to reset its price in each period. Then, the aggregate price level p_t evolves according to:

$$p_t = \gamma p_{t-1} + (1-\gamma)\, q_t.$$

Or, equivalently,

$$\pi_t = (1-\gamma)\,(q_t - p_{t-1}) = \frac{1-\gamma}{\gamma}\,(q_t - p_t)\,, \tag{1}$$

where q_t denotes the index for all newly set prices in period t. The first equality of (1) says only newly set prices matter for inflation because other prices are fixed. The second equality gives a relationship between the newly set relative price and overall inflation under sticky prices with random duration. Here, $-\pi_t = p_{t-1} - p_t$ can be interpreted as the relative price of non-price-setting firms in period t. Given that the all firms' relative prices sum to 0, we must have $-\gamma\pi_t + (1-\gamma)\,(q_t - p_t) = 0$, which gives us the second equality of (1).

Gali and Gertler (1999) depart from the pure forward-looking sticky price model by assuming the presence of two types of firms. A fraction $1-\phi$ of firms adjust a price in period t and set its price optimally. The remaining firms are backward-looking and use a simple rule of thumb. Then, the price index q_t is expressed as a linear combination of the price set by forward-looking firms (p_t^f) and the price set by backward-looking firms (p_t^b):

$$q_t = (1-\phi)p_t^f + \phi p_t^b, \tag{2}$$

where p_t^f and p_t^b are given by:

$$p_t^f = (1-\gamma)\sum_{j=0}^{\infty}\gamma^j E_t(mc_{t+j}^n) \tag{3}$$

$$p_t^b = q_{t-1} + \pi_{t-1}, \tag{4}$$

where mc_t^n is nominal marginal cost in period t.[2]

We substitute (3) and (4) into (2) and then using (1), we obtain:[3]

$$\pi_t = \frac{1-\gamma}{\gamma}\left\{(1-\phi)(1-\gamma)\sum_{j=0}^{\infty}\gamma^j E_t(mc_{t+j}^n - p_t) + \phi\left(\frac{1}{1-\gamma}\pi_{t-1} - \pi_t\right)\right\}.$$

[2]We set the discount factor to unity for simplicity.

[3]Above, we use the fact that $p_t^b - p_t = q_{t-1} + \pi_{t-1} - p_t = (q_{t-1} - p_{t-1}) + \pi_{t-1} - \pi_t = \frac{1}{1-\gamma}\pi_{t-1} - \pi_t$.

Solving this equation for π_t yields:

$$\pi_t = \tilde{\rho}\pi_{t-1} + \zeta_1(1-\gamma)\sum_{j=0}^{\infty}\gamma^j E_t(mc_{t+j} - h_{t,j}), \tag{5}$$

where $\tilde{\rho} = \phi/(\phi+\gamma-\gamma\phi)$, $\zeta_1 = ((1-\phi)(1-\gamma))/(\phi+\gamma-\gamma\phi)$, and $h_{t,j} = -(\pi_{t+1} + ... + \pi_{t+j})$. Here, mc_t is real marginal cost given by $mc_t = mc_t^n - p_t$.

This expression gives the aggregate Euler pricing equation in terms of the weighted average of current and future nominal marginal costs deflated by the current price level.[4] Due to the backward-looking firms, lagged inflation matters for inflation dynamics. In addition, the second term implies that inflation is affected by the discounted sequence of future nominal marginal costs deflated by the current price level. Obviously, this is due to forward-looking firms.

2.2 The dual stickiness model

Suppose that each firm faces infrequent information updating as well as price setting. We assume that each firm adjusts its price with a constant probability $1-\gamma$ and then sets its price optimally using all available information with a probability $1-\phi$. The remaining firms have old information, given the timing of information updating. Thus, the law of large numbers implies a fraction $1-\phi$ of firms that adjust prices in period t set their price optimally while the remaining firms adjust using stale information. For simplicity, we assume each 'stickiness' is independent of the other.[5]

Whereas the set of assumptions permits us to use (1) - (3), we depart from Gali and Gertler (1999) by replacing backward-looking firms with inattentive firms which have outdated information but otherwise set their price optimally. In particular, p_t^b under the dual

[4]Note that it is straightforward to see that nominal marginal cost deflated by the current price level $mc_{t+j} - h_{t,j}$ is identical to $mc_{t+j}^n - p_t$ from the definition of $h_{t,j}$.

[5]We assume the independence of the probabilities for tractability. While we admit that relaxing the independence assumption may be an important step for an extension of the model, this is beyond the scope of the paper.

stickiness model is given by:

$$p_t^b = (1-\phi)\sum_{k=0}^{\infty}\phi^k E_{t-k-1}(p_t^f), \tag{6}$$

instead of (4). Note that p_t^b consists of individual prices based on stale information. The expression inside the brackets represents each individual price for inattentive firms with a $k+1$ period old information set for $k = 0, 1, 2, ...$

Note that the firms with different information sets are distributed in the same way as Mankiw and Reis (2002). Combining (2) and (6), we obtain:

$$q_t = (1-\phi)\sum_{k=0}^{\infty}\phi^k E_{t-k}(p_t^f).$$

Thus, the formulation of the price index q_t is identical to the sticky information model by Mankiw and Reis (2002), except that each individual price is determined in a forward-looking manner.

The dual stickiness model is similar to the hybrid sticky price model. Using the fact that $mc_{t+j}^n = \Delta mc_{t+j}^n + mc_{t-j-1}^n$, Eq. (6) can be expressed :

$$p_t^b = q_{t-1} + (1-\phi)\sum_{k=0}^{\infty}\phi^k\left[(1-\gamma)\sum_{j=0}^{\infty}\gamma^j E_{t-k-1}(\Delta mc_{t+j}^n)\right]. \tag{7}$$

Comparing (4) and (7), only the difference is in the second term. While the second term of (4) is lagged inflation the corresponding term in (7) is the cross-sectional (weighted) average of the discounted sum of expected nominal marginal cost growth, conditional on old information. When the cross-sectional average conditional on old information is close to lagged inflation, both models' inflation dynamics will be similar.

Using (1), (2), (3), and (7) to eliminate q_t, p_t^f, and p_t^b, we obtain the equation we estimate:

$$\begin{aligned}\pi_t = {} & \rho\pi_{t-1} + \zeta_1(1-\gamma)\sum_{j=0}^{\infty}\gamma^j E_t(mc_{t+j} - h_{t,j}) \\ & + \zeta_2(1-\phi)\sum_{k=0}^{\infty}\phi^k(1-\gamma)\sum_{j=0}^{\infty}\gamma^j E_{t-k-1}(\Delta mc_{t+j} + \pi_{t+j}),\end{aligned} \tag{8}$$

where $\rho = \gamma\tilde{\rho}$, $\zeta_2 = \frac{\phi(1-\gamma)}{\gamma+\phi-\gamma\phi}$. Here, we use $\Delta mc_{t+j}^n = \Delta mc_{t+j} + \pi_t$.

This equation has two similarities with (5). First, both models have the discounted sum of nominal marginal costs deflated by the current price level in the second term of the equation.

Second, lagged inflation matters for current inflation. The effect of the lagged inflation on current inflation is a little weaker under the dual stickiness model than the hybrid model because $\tilde{\rho} \geq \rho$.

However, there is an important difference that allows us to distinguish the two. The dual stickiness model has another source of inflation inertia. The third term on the right hand side of (5) contributes to inflation inertia through information delay. If the combined effect of the first and third term in (8) is similar to the effect of the first term in (5), the inflation dynamics in the dual stickiness model is close to those in the hybrid model. Thus, a key identifying feature of the dual stickiness relative to the hybrid model is the additional term that corresponds to lagged conditional expectations.

Note that the dual stickiness model nests the pure sticky information model as well as the pure forward-looking sticky price model. Suppose that there are no inattentive firms in the economy ($\phi = 0$). Then, the dual stickiness model reduces to the pure forward-looking sticky price model as well as the hybrid model. Suppose that firms can reset a price every period with probability one ($\gamma = 0$). Then, (8) reduces to the sticky information Phillips curve:

$$\pi_t = \frac{1-\phi}{\phi} mc_t + (1-\phi) \sum_{j=0}^{\infty} \phi^k E_{t-k-1}[\Delta mc_t + \pi_t]. \quad (9)$$

Thus, our dual stickiness model is comparable to alternative pricing models: the model of pure sticky information and price directly and the hybrid model via the presence or absence of the third term of (8).

3 Empirical Implementation

We estimate (5) and (8) using the two step approach proposed by Sbordone (2002), Woodford (2001) and Ruud and Whelan (2005a). In the first step estimation, we run a vector-autoregression (VAR) to obtain the predicted series of labor share and inflation in the aggregate Euler equation for inflation (5) and (8). Given the VAR process, the second step minimizes the variance of a distance between the model's and actual inflation. Our estimated parameters are the probability of resetting a price $1 - \gamma$ and of updating information $1 - \phi$

(or a fraction of forward-looking firms).

Our two step approach slightly differs from the previous studies in that we do not estimate the closed form solution to the aggregate Euler pricing equation. Sbordone (2002) transforms the standard NKPC into the closed form solution to the logarithm of the price - unit labor cost ratio and estimates the parameters of interest. Woodford (2001) and Ruud and Whelan (2005a) rewrite the NKPC as the forward-looking solution to inflation and estimate parameters by minimizing the distance between the models' and actual inflation. Our second step also minimizes the distance between model's and actual inflation, but uses a non-closed form of inflation (5) and (8). We estimate the non-closed form equation because it is generally impossible to derive for the closed form solution to the dual stickiness model, due to infinitely many lagged expectation terms in (8). While it is straightforward to estimate the closed form for the hybrid model, as in the previous studies, the transformation of the hybrid model to the closed form changes the estimation equation in an incomparable form to the dual stickiness model. As such, there is a possibility of unfair comparisons between the dual stickiness model and its alternatives. Therefore, we use (5) and (8) to estimate parameters and put a restriction in the case for the pure sticky price model (i.e., $\phi = 0$) and the pure sticky information model (i.e., $\gamma = 0$).

We specify the forecasting model by introducing the vector X_t in the following VAR:

$$X_t = AX_{t-1} + \epsilon_t. \tag{10}$$

In the benchmark case, the vector X_t includes labor share, inflation and the output gap. We include the output gap in X_t because it has strong forecasting power for labor share and inflation as Ruud and Whelan (2005a) show. The vector X_t also includes lags of the three variables. In general, X_t is given by a $(3p \times 1)$ vector of $[x_t, x_{t-1}, \cdots, x_{t-p+1}]'$, where $x_t = [mc_t, \pi_t, y_t]'$ and y_t is the output gap.

Next, we calculate a series of the theoretical inflation given the forecasting process (10). Ordinary least squares produce a consistent estimate of the coefficient matrix $\hat{A}$. Let e_{mc} and e_π denote a selection vector with $3p$ elements. All elements are zero except the first element of e_{mc} and the second element of e_π, which are unity. Given the definitions, we express labor share and inflation as $e'_{mc}X_t$ and $e'_\pi X_t$, respectively.

For expositional purposes, consider a special case with $\gamma = 0$ (i.e., (9)). Given the definitions of selection vectors, $E_{t-k-1}(\Delta mc_t + \pi_t) = (e'_{mc}(A - I) + e'_{\pi}A)A^k X_{t-k-1}$. Then, (9) can be written as:

$$\pi_t^m(\theta, A) = \frac{1-\phi}{\phi} mc_t + (1-\phi)(e'_{mc}(A - I) + e'_{\pi}A) \sum_{k=0}^{\infty} \phi^k A^k X_{t-k-1}, \tag{11}$$

where $\pi_t^m(\theta, A)$ denotes the inflation predicted by the model and θ denotes the parameter vector to be estimated. In this particular case, $\theta = \phi$. By introducing an arbitrary truncation value of K, we approximate this equation by:

$$\pi_t^m(\theta, A) = \frac{1-\phi}{\phi} mc_t + (1-\phi)(e'_{mc}(A - I) + e'_{\pi}A) \sum_{k=0}^{K-1} \phi^k A^k X_{t-k-1}. \tag{12}$$

When the model explains the data well, $\pi_t^m(\theta, A)$ is close to actual inflation. Using a consistent estimate $\hat{A}$, we choose the parameter θ by:

$$\hat{\theta} = \text{Argmin}_{\theta} \quad var(\pi_t - \pi_t^m(\theta, \hat{A})). \tag{13}$$

We use the same procedure to estimate (5) and (8). Given the VAR process, the series of $\{X_{t-k}\}_{k=0}^{\infty}$ suffice to express all discounted sums in (5) and (8). Appendix A proves (5) and (8) can be respectively expressed as:

$$\pi_t^m(\theta, A) = \tilde{\rho}\pi_{t-1} + b' X_t, \tag{14}$$

$$\pi_t^m(\theta, A) = \rho\pi_{t-1} + b' X_t + c' \sum_{k=0}^{\infty} \phi^k A^k X_{t-k-1}, \tag{15}$$

where $b' = \zeta_1[(1-\gamma)e'_{mc} + \gamma e'_{\pi}A][I - \gamma A]^{-1}$ and $c' = \zeta_2(1-\gamma)(1-\phi)\,[e'_{mc}\,(A - I) + e'_{\pi}A]\,[I - \gamma A]^{-1}$. The parameter space is $\theta = [\gamma, \phi]'$. Once again, we choose an arbitrary large truncation parameter K and minimize the variance of the distance between model and actual inflation.

To make statistical inferences, we use a bootstrap method because the forecasted variables in the second step are "generated regressors" and thus the standard asymptotic standard errors calculated from nonlinear least squares are incorrect. A bootstrap method is useful for making statistical inferences rather than corrected asymptotic standard errors because of the complicated estimation equation (15).

To conduct the bootstrap, we first generate 399 bootstrapped series of $X^*_{i,t}$ from the empirical distribution of the residual $\hat{\epsilon}_t$ and the coefficient estimate $\hat{A}$ in (10). Using the resampled $X^*_{i,t}$, we estimate structural parameters θ_i by minimizing the variance of $\pi^*_{i,t} - \pi^{*m}_{i,t}(\theta_i, \hat{A})$ for $i = 1, 2, ..., 399$. We compute the covariance matrix of $\hat{\theta}_i$.[6]

We use quarterly US data between 1960:1 and 2005:2. Inflation is measured as the log difference of the implicit GDP deflator. Labor share, which measures marginal cost, is the log of (NFB unit labor cost/NFB price deflator). The output gap is the quadratically detrended real GDP.

3.1 Benchmark Results

Table 1 shows the estimation results. In our benchmark case, we use the VAR with three lags and the truncation parameter of $K = 12$. We report the estimates from four models: i) the dual stickiness model with price and information stickiness (DS), ii) the hybrid model (Hybrid) iii) the pure forward-looking sticky price model (FL), and iv) the pure sticky information Phillips curve à la Mankiw and Reis (2002) (MR). The 95 percent confidence intervals appear in brackets.

Six features in Table 1 are worth emphasizing. First, both probabilities are significantly different from zero under the dual stickiness model, suggesting that both types of stickiness matter for the aggregate inflation dynamics. Our benchmark case suggests that 11-20 percent of firms change prices every period, but only 12-54 percent of these firms use the latest information to determine prices. Evaluated at the point estimates, the former is 15 percent and the latter is 39 percent, suggesting that only 5.8% in the economy choose the optimizing price.

Second, our results for the hybrid model are consistent with Gali and Gertler (1999)

[6] MacKinnon (2002) gives detailed explanations for the bias-corrected bootstrap intervals. To obtain 95 percent confidence intervals of estimates, we compute the bias-corrected bootstrap interval $[2\hat{\theta} - \bar{\theta}^* - 1.96 s^*_{\theta}, 2\hat{\theta} - \bar{\theta}^* + 1.96 s^*_{\theta}]$, where $\hat{\theta}$, $\bar{\theta}^*$, and s^*_{θ} denote the original estimate from the actual data, the sample mean of the bootstrap estimate $\hat{\theta}^*_i$, and the standard deviation of $\hat{\theta}^*_i$, respectively.

Table 1: Estimates of the four aggregate Euler equations

	γ	ϕ	ρ or $\tilde{\rho}$	$\bar{R}^2$	$\text{var}(\pi_t - \hat{\pi}_t))$
DS	0.8510	0.6078	0.5493	0.8311	0.0631
	[0.8034, 0.8916]	[0.4624, 0.8818]	[0.4319, 0.7756]		
Hybrid	0.8675	0.5370	0.5721	0.8336	0.0622
	[0.8330, 0.8996]	[0.4132, 0.7746]	[0.4478, 0.8124]		
FL	0.8742	0.00	0.00	0.7024	0.1112
	[0.8389, 0.9079]	-	-		
MR	0.00	0.8933	0.00	0.6491	0.1311
	-	[0.8553, 0.9230]	-		

NOTES: Estimation from 1960:1 to 2005:2. The trivariate VAR(3) ($[mc_t, \pi_t, y_t]'$) is estimated over 1957:Q2 - 2005:Q2 in the first step. The 95 percent bootstrap confidence intervals are in brackets. The parameter γ denotes the probability of price fixity. The parameter ϕ denotes the probability of information fixity in the dual stickiness model or the fraction of backward-looking firms. The last column, $\text{var}(\pi_t - \hat{\pi}_t)$, is the variance of the distance where $\pi_t^m(\theta, \hat{A})$ is evaluated at the obtained estimates. DS, Hybrid, FL and MR stand for the dual stickiness model, the hybrid model, the pure forward-looking sticky price model, and the pure sticky information model, respectively.

and Gali, Gertler, and López-Salido (2005). They emphasize key parameters for properly assessing importance of forward- versus backward-looking behavior is γ_f and γ_b, which are a function of the estimated parameters γ and ϕ.[7] While they conclude γ_f is roughly 0.65 and $\gamma_b = 0.35$, our estimates imply $\gamma_f = 0.62$ and $\gamma_b = 0.38$, regardless of our difference in the estimation strategy. In addition, the influence of backward-looking behavior is statistically significant and improves the goodness-of-fit of the sticky price model. This finding is also consistent with Gali and Gertler and many others.

Third, interestingly, the estimated parameters γ and ϕ under the dual stickiness model are quite close to the estimated parameters under the hybrid model, regardless of different interpretations on ϕ. Indeed, there is no substantial difference in these parameters including the coefficients of lagged inflation. As we expect, the effect of lagged inflation on current inflation is slightly weaker under the dual stickiness model (0.55) than under the hybrid model (0.57). In addition, the slightly higher ϕ in the dual stickiness model (0.60) may explain the remaining part of inflation inertia that lagged inflation in the hybrid model can explain.

Fourth, the frequency of information updating $1 - \phi$ under the dual stickiness model is somewhat high relative to that in the pure sticky information Phillips curve and those in previous studies (where prices themselves are completely flexible). Our estimate of the information updating probability is about 39 percent. On the other hand, the probability of information updating is about 11 percent in the pure sticky information model. Other studies such as Kahn and Zhu (2006) estimate the probability in the range of 12 to 35 percent, using forecasted series for the output gap. Under the marginal cost version of the sticky information model, the estimate is roughly 15 percent in Andrés, López-Salido, and Nelson (2005) and 20 percent in Korenok (2005).[8] Our relatively high frequency of information updating could be interpreted as arising from the substitution of price stickiness

[7] According to their definitions, $\gamma_f = \gamma/(\gamma + \phi)$ and $\gamma_b = \phi/(\gamma + \phi)$ when the discounted factor equals unity.

[8] There are several reasons why our estimate from the pure sticky information Phillips curve differs from the previous studies – especially Kahn and Zhu (2006). First, we use different specifications of VARs. Second, we use labor share rather than the output gap. Third, we use in-sample forecasts of inflation and labor share rather than out-of-sample forecasts of inflation and the output gap.

for information stickiness.

Fifth, we find that price stickiness substitutes for information stickiness substantially but the latter does so for the former only modestly. In particular, if one extends the sticky information model to the dual stickiness model, the reduction of the information fixity is about 28 percent (from 0.89 to 0.61). On the other hand, if one extends the pure forward-looking sticky price model to the dual stickiness model, the reduction of the price fixity is only 2 percent (from 0.87 to 0.85). The low substitution may suggest that sticky prices are difficult to be replaced with sticky information.

Finally, we assess the goodness-of-fit of the four models from the adjusted R^2. The ordering of the models in terms of the goodness-of-fit is the hybrid, the dual stickiness, the pure forward-looking sticky price, and the sticky information model. Overall, the models with lagged inflation (the hybrid and dual stickiness models) perform similarly. A comparison between the pure sticky price and information models favors the pure sticky price model. The latter result is consistent with Korenok (2005).

The assessment can be done visually by looking at the path of the models' inflation. Figures 1-4 plot actual inflation and inflation predicted by the four models between 1960:1 and 2005:2. Due to the presence of lagged inflation, the figures demonstrate that the inflation series generated by the hybrid and dual stickiness models closely track actual inflation. The pure sticky price and information models track actual inflation roughly. The dual stickiness model closely tracks actual inflation because it endogenously generates lagged inflation in its pricing Euler equation.

3.2 Relative importance of information and price stickiness

Using our estimation results, we next quantify the relative importance of information and price stickiness. We compute the percentage reduction in the variance of the distance between actual inflation and the theoretical inflation when we add another type of stickiness into either pure forward-looking NKPC or the pure sticky information Phillips curve. This is summarized in Table 2. For example, we can see from Table 1 that the variance of the pure forward-looking NKPC is 0.11. If one adds sticky information into the model, the model turns out to be the dual stickiness model whose variance is 0.06. Hence, the percentage reduction

Figure 1: The inflation predicted by the purely forward-looking NKPC

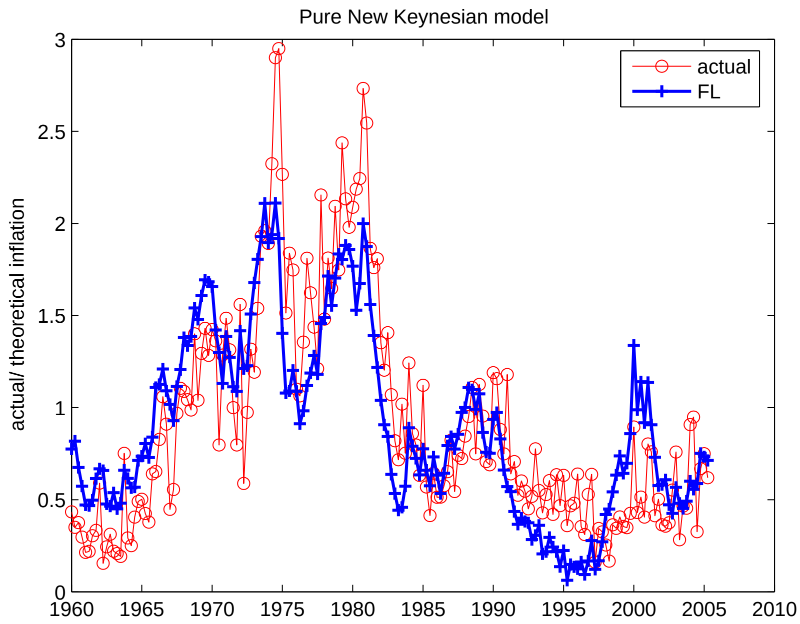


Figure 2: The inflation predicted by the hybrid NKPC

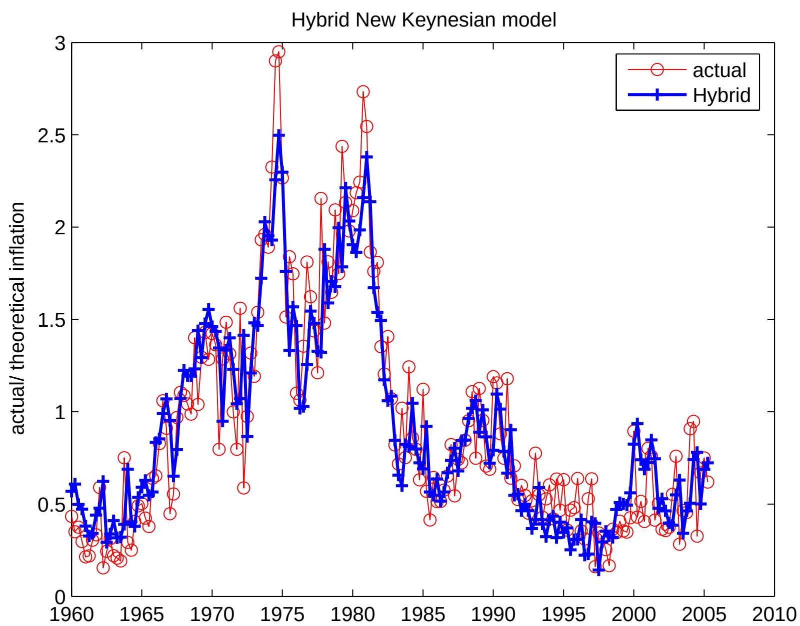


Figure 3: The inflation predicted by the Mankiw and Reis sticky information model

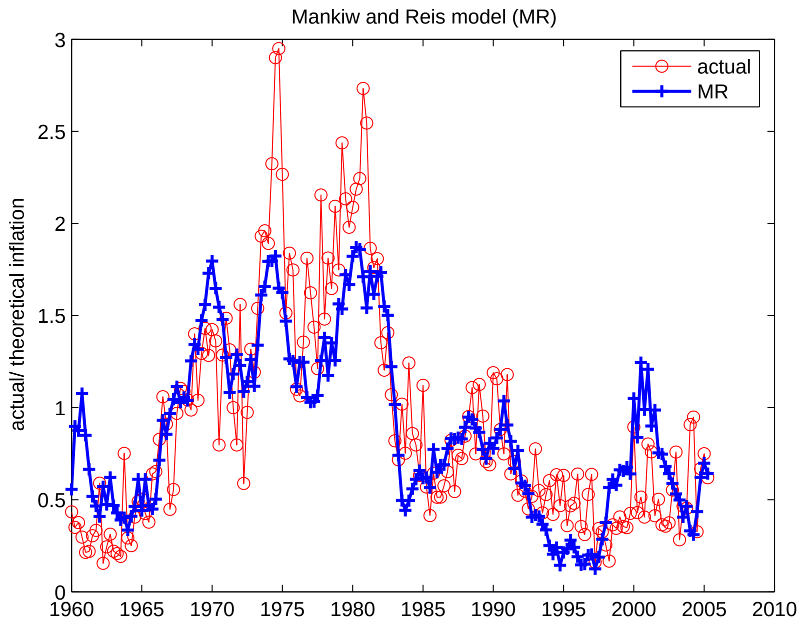


Figure 4: The inflation predicted by the dual stickiness model

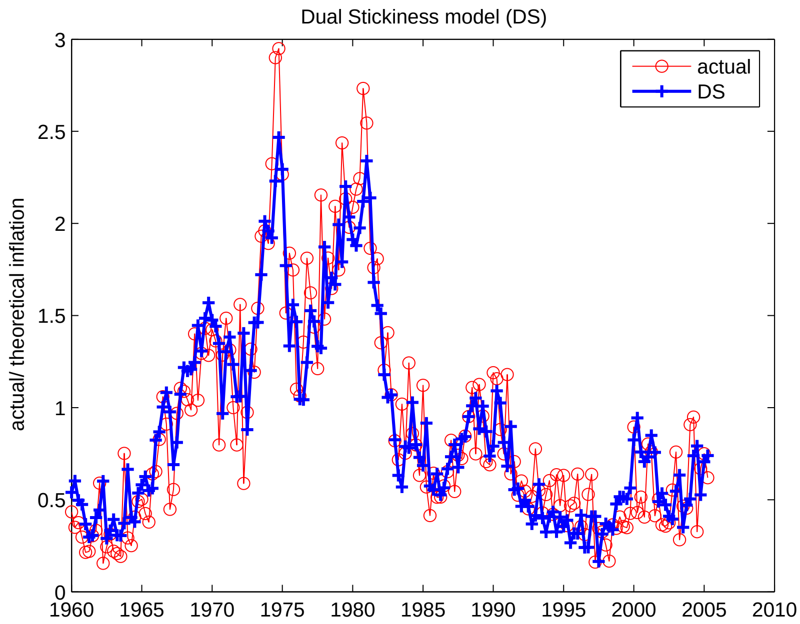


Table 2: Percentage reduction of var($\pi_t - \hat{\pi}_t$) from a single to the dual stickiness model

relative importance	
Sticky information (FL → DS)	43.3%
Sticky Prices (MR → DS)	51.9%

in the variance is -(0.06 - 0.11)/0.11 $\simeq$ 43 percent. In other words, adding sticky information contributes to 43 percent reduction of the variance of residuals in the pure forward-looking NKPC. On the other hand, if sticky prices are added into the sticky information model, one can see from Table 1 that the percentage reduction in the variance of the sticky information Phillips curve is 52 percent. While both types of stickiness play a non-negligible important role for the aggregate inflation dynamics, adding sticky prices beats adding sticky information in terms of the percentage reduction of the variance of the residuals.

3.3 Sub-sample analysis

As a robustness check, we estimate the models over different sub-samples, shown in Table 3.[9] Our estimation strategy implicitly assumes that the unrestricted forecasting process of X_t (i.e., the coefficient matrix A) is invariant over the whole sample. However, this assumption could be questionable, because a shift in policy alters the dynamic path of a macroeconomic variable in its reduced form and affects the economic agents' forecasts. As such, we consider the following three sub-samples: 1960:Q1 - 1982:Q4, 1979:Q4 - 2005:Q2, and 1983:Q1 - 2005:Q2. The first and last sub-samples represent high inflation and low inflation eras in the U.S. economy. The second sub-sample reflects a major policy shift by Federal Reserve Chairman Paul Volcker in October 1979.

[9] We also conducted the robustness analysis to the truncation parameter K and the different specifications of the VAR such as the lag length and the inclusion of the federal funds rate and term spread. These robustness checks revealed that parameter estimates and the goodness-of-fit remain essentially unaltered. In particular, as for the change in K, the estimates remain unaltered unless K is small (e.g., $K \leq 3$). The increase in the lag length of the VAR enhances the performance of the pure forward-looking NKPC slightly, but the adjusted coefficient of determination of the other three models remains low relative to the other models.

Table 3: Robustness to sub-samples

	γ	ϕ	ρ or $\tilde{\rho}$
DS			
1960:Q1 - 1982:Q4	0.8228	0.3389	0.3158
	[0.5178, 1.0242]	[0.1048, 0.7373]	[0.1099, 0.6733]
1979:Q4 - 2005:Q2	0.8818	0.3843	0.3655
	[0.8475, 0.9123]	[0.2655, 0.8535]	[0.2532, 0.8080]
1983:Q1 - 2005:Q2	0.9126	0.4177	0.4017
	[0.8946, 1.0090]	[0.0360, 0.7204]	[0.0815, 0.6779]
Hybrid			
1960:Q1 - 1982:Q4	0.8289	0.3163	0.3582
	[0.7829, 0.8678]	[0.1066, 0.6675]	[0.1319, 0.7455]
1979:Q4 - 2005:Q2	0.8856	0.3567	0.3851
	[0.8555, 0.9155]	[0.2507, 0.7724]	[0.2692, 0.8306]
1983:Q1 - 2005:Q2	0.9152	0.3874	0.4086
	[0.9003, 0.9958]	[0.0611, 0.6598]	[0.0680, 0.6822]

NOTES: The sub-sample 1960:Q1 - 1982:Q4 uses a VAR(3) sample over 1957:Q2 - 1982:Q4. The sub-sample 1979:Q4 - 2005:Q2 uses a VAR(3) sample over 1977:Q1-2005:Q2. The final sub-sample 1983:Q1 - 2005:Q2 uses a VAR(3) sample over 1980:Q2 - 2005:Q2. Other characteristics are explained in the footnote of Table 1.

In Table 3, the estimated probabilities in the dual stickiness model are stable over the sub-samples. Interestingly, price stickiness is insensitive to the sub-sample analysis. Information stickiness is somewhat lower over the sub-samples than over the full sample. Because the differences are statistically insignificant, the change in the coefficient matrix of the VAR does not significantly affect information stickiness.

The parameter estimates in the hybrid model also have stable patterns. Again, the estimates of the fraction of backward-looking firms are lower over the sub samples than over the full sample, but price stickiness is robust to the sub sample analysis. The implied γ_f and γ_b are about 0.71 and 0.29 over the three sub-samples, respectively.

4 General Equilibrium Comparisons

Finally, we compare the dual stickiness and hybrid models by placing each in a dynamic equilibrium model. We then compare the impulse responses to a monetary policy shock under each inflation equation.

Erceg, Henderson and Levin's (2000) sticky wage and price model will serve as the economic environment. To conserve space, we present the log-linearized equations from their model rather than a complete description of the consumer's and firm's problems and market clearing conditions.

Let w_t, ξ_t and Δm_t denote nominal wage inflation, the real wage and the nominal money growth rate. Excluding the price inflation equation, the system consists of

$$\Delta m_t - \Delta y_t = \pi_t \tag{16}$$

$$\Delta m_t = \delta \Delta m_{t-1} + \varepsilon_t \tag{17}$$

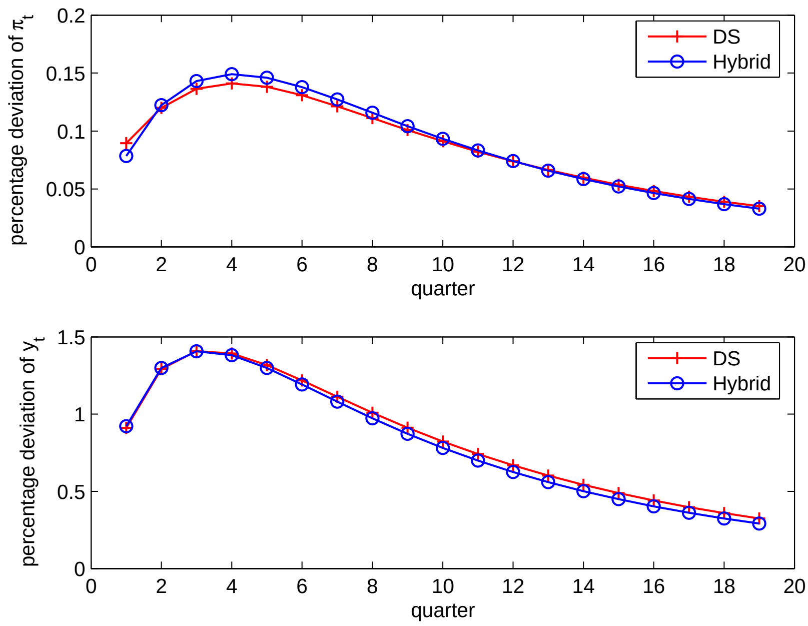
$$\Delta \xi_t = w_t - \pi_t \tag{18}$$

$$w_t = E_t\left(w_{t+1}\right) + \kappa\left(s_t - \xi_t\right) \tag{19}$$

Equation (16) is the growth rate form of the quantity theory of money (or cash-in-advance constraint). Equation (17) is the monetary policy rule. Money growth is first-order autoregressive with a white noise innovation. Equation (18) states that an increase in the real wage is equal to wage inflation net of price inflation.

The final expression determines nominal wage growth. Here, s_t is the household marginal rate of substitution between consumption and leisure; therefore, $s_t - \xi_t$ is the household's wedge between return to and cost of supplying labor.

Figure 5: Impulse Responses to a Monetary Shock



NOTES: Impulse response functions for inflation (the upper panel) and output (the lower panel) to a one percent innovation to the money growth rate.

If period utility depends only on current consumption and leisure and production depends solely on labor, then the marginal rate of substitution is a function of only output, $s_t = \theta y_t$. Our baseline parameters for these equations are: $\kappa = 0.02, \theta = \delta = 0.5$.

Only the price inflation equation remains to be specified. We consider inflation equations from the hybrid and the dual stickiness models. Holding fixed equations (16)-(19), we report impulse responses to a positive unit shock to ε_t for both models. We use the point estimates from Table 1 to conduct the analysis.[10]

In post-WWII U.S. data, Christiano, Eichenbaum and Evans (2005) and others use a recursive vector-autoregression to study the economy's response to a monetary shock. In response to an expansionary shock, output gradually increases and then peaks after approximately six quarters. Inflation also increases gradually and then peaks after approximately eight quarters.[11]

Figure 5 plots output and inflation for both specifications. The impulse responses are generally similar. Each output response peaks in the third quarter following the shock. The output responses are similar along the entire path.

The inflation responses have similar peaks in both magnitude and timing. Both peak between in the fourth quarter following the shock. None approach the eight quarter peak found in the data. Both return to the steady state at similar rates. Thus, the two models deliver qualitatively similar dynamics in this equilibrium monetary model.

5 Related Research

Mankiw, Reis and Wolfers (2003) use sticky information to explain the cross sectional and time series behavior of inflation expectations from survey data. Carroll (2003) uses an epidemiological model of information transmission to also study expectations survey data. His model delivers stickiness in expectations. Our paper's results are starkly different. Differences between survey versus statistically constructed expectations measures merit further research.

Khan and Zhu (2006) estimate a sticky information model with random information updating. Lagged expectations of current variables are constructed using a VAR, as we do. They estimate that information is updated, on average, annually. While instructive, their analysis does not speak to our question because: (i) marginal cost is measured with the

[10]Each price inflation equation depends upon marginal cost (mc). In our equilibrium model, $mc_t = \xi_t - \mu y_t$ and μ is the elasticity marginal rate of transformation with respect to output. Based on Erceg et.al., we set $\mu = 0.43$.

[11]These qualitative findings have been documented by other researchers, including Estrella and Fuhrer (2002), Gali (1992) and Stock and Watson (2001).

output gap and (ii) their specification does not include sticky prices. Kiley (2005) separately estimates sticky price and sticky information using maximum likelihood, which he then compares to a reduced form forecasting regression. The sticky information model performs slightly better. However, both it and the sticky price model improve dramatically once a 'backward looking' component is added.

Rotemberg and Woodford (1997) modify a Calvo sticky price model to allow for information stickiness. In it, each firm with the opportunity to reset its price is randomly assigned to use either current period or last period's information to set its price. They estimate that a price setter uses old information with probability 0.37.

Korenok (2005) estimates both sticky price and information models and also uses labor share to proxy marginal cost. Rather than use two-steps (i.e. first estimate the variables driving process and then the parameters of interest), he combines these into a single step Bayesian procedure that leads to a more efficient estimator. In each model, he finds similar probabilities of updating as in previous studies, but tighter confidence intervals than those studies. He then combines models and conducts a non-structural, multiple specification analysis. His empirical comparison favors the sticky price model.

6 Conclusion

The paper's title posed the question, "Do Sticky Prices Need to Be Replaced with Sticky Information?" One mechanism that previous researchers (notably Mankiw and Reis, 2002) have offered as a replacement for sticky prices is sticky information. Using comparable data series, time periods, and estimation strategies, we found that a hybrid sticky price model outperforms the sticky information – flexible price model in terms of goodness of fit. Thus, the direct answer to our original question is that sticky price models need not be abandoned.

We also developed a new model that incorporates both sticky information and prices. This dual stickiness and the hybrid models perform equally well in terms of goodness of fit and implied general equilibrium dynamics. We demonstrated that the two models generate similar inflation dynamics on several dimensions.

The dual stickiness model's main advantage is that it does not rely on backward-looking behavior. In our view, the strong empirical support for the presence of backward-looking firms can be interpreted as the presense of inattentive sticky information firms. Every firm updates its information infrequently, approximately once every seven months according to our estimates. As such, dual stickiness may provide more plausible microeconomic foundations.

Our dual stickiness model could be extended straightforwardly and realistically to allow for correlation between the likelihood of information and price updating. It is natural to believe that firms often change their price in the same period that they receive new information. We conjecture that the fit of the dual stickiness model would improve with this extension.

Also, integrating real rigidities into the model is a promising direction. This may improve our slightly low estimated probabilities of price change and information updating. In addition, our model can be extended to jointly estimate nominal price and wage stickiness under infrequent information updating. Finally, monetary policy analysis under the dual stickiness model is an important step for future research.

A Derivation of (14) and (15)

This appendix derives (14) and (15) from the aggregate Euler equation (5) and (8), given the VAR process (10). In what follows, we focus on (15).

The second term of the right-hand side of (8) is

$$\zeta_1(1-\gamma)\sum_{j=0}^{\infty}\gamma^j E_t\left[mc_{t+j}-h_{t,j}\right]. \tag{20}$$

Note that

$$mc_{t+j}-h_{t,j}=\begin{cases} mc_t & \text{for } j=0 \\ mc_{t+j}+\pi_{t+1}+\cdots+\pi_{t+j} & \text{for } j\geq 1 \end{cases}. \tag{21}$$

Our definition of the selection vectors e_{mc} and e_π implies:

$$
\begin{aligned}
& \zeta_1(1-\gamma)\sum_{j=0}^{\infty}\gamma^j E_t\left[mc_{t+j}-h_{t,j}\right] \\
= \quad & \zeta_1(1-\gamma)\sum_{j=0}^{\infty}\gamma^j E_t\left[e'_{mc}X_{t+j}\right]+\zeta_1(1-\gamma)\sum_{j=1}^{\infty}\gamma^j e'_\pi E_t(X_{t+1}+X_{t+2}+\cdots+X_{t+j}) \\
= \quad & \zeta_1(1-\gamma)\sum_{j=0}^{\infty}\gamma^j\left[e'_{mc}A^jX_t\right]+\zeta_1(1-\gamma)\sum_{j=1}^{\infty}\gamma^j e'_\pi(A+A^2+\cdots+A^j)X_t.
\end{aligned}
$$

The first term of this equation equals $\zeta_1(1-\gamma)e'_{mc}[I-\gamma A]^{-1}X_t$. One can write the second term as follows:

$$
\begin{aligned}
& \zeta_1(1-\gamma)\sum_{j=1}^{\infty}\gamma^j e'_\pi(A+A^2+\cdots+A^j)X_t \\
= \quad & \zeta_1(1-\gamma)\gamma e'_\pi A\sum_{j=0}^{\infty}\gamma^j(I+A+A^2+\cdots+A^j)X_t \\
= \quad & \zeta_1(1-\gamma)\gamma e'_\pi A \\
& \times[(1+\gamma+\gamma^2+\cdots)I \\
& +(1+\gamma+\gamma^2+\cdots)\gamma A \\
& +(1+\gamma+\gamma^2+\cdots)\gamma^2A^2+\cdots]X_t \\
= \quad & \zeta_1\gamma e'_\pi A[I-\gamma A]^{-1}X_t.
\end{aligned}
$$

Therefore, (20) is summarized by a column vector b such that

$$
b'X_t=\zeta_1(1-\gamma)\sum_{j=0}^{\infty}\gamma^j E_t\left[mc_{t+j}-h_{t,j}\right], \tag{22}
$$

where $b'=\zeta_1[(1-\gamma)e'_{mc}+\gamma e'_\pi A][I-\gamma A]^{-1}$.

Next, the third term of the right hand side of (8) is

$$
\zeta_2\psi\sum_{k=0}^{\infty}\phi^k\sum_{j=0}^{\infty}\gamma^j E_{t-k-1}[\Delta mc_{t+j}+\pi_{t+j}],
$$

where $\psi=(1-\gamma)(1-\phi)$. For $k\geq 0$,

$$
\begin{aligned}
E_{t-k-1}[\Delta mc_{t+j}+\pi_{t+j}] &= E_{t-k-1}\left[mc_{t+j}-mc_{t+j-1}+\pi_{t+j}\right] \\
&= E_{t-k-1}\left[e'_{mc}X_{t+j}-e'_{mc}X_{t+j-1}+e'_\pi X_{t+j}\right] \\
&= e'_{mc}A^{j+k+1}X_{t-k-1}-e'_{mc}A^{j+k}X_{t-k-1}+e'_\pi A^{j+k+1}X_{t-k-1} \\
&= \left[e'_{mc}(A-I)+e'_\pi A\right]A^{j+k}X_{t-k-1}.
\end{aligned}
$$

Therefore, we obtain

$$
\begin{aligned}
&\zeta_2\psi\sum_{k=0}^{\infty}\phi^k\sum_{j=0}^{\infty}\gamma^j E_{t-k-1}[\Delta mc_{t+j}+\pi_{t+j}] \\
=&\zeta_2\psi\sum_{k=0}^{\infty}\phi^k\sum_{j=0}^{\infty}\gamma^j\left[e'_{mc}(A-I)+e'_{\pi}A\right]A^{j+k}X_{t-k-1} \\
=&\zeta_2\psi\left[e'_{mc}(A-I)+e'_{\pi}A\right]\sum_{j=0}^{\infty}\gamma^j A^j\sum_{k=0}^{\infty}\phi^k A^k X_{t-k-1} \\
=&c'\sum_{k=0}^{\infty}\phi^k A^k X_{t-k-1},
\end{aligned}
$$

where $c' = \zeta_2\psi\left[e'_{mc}(A-I)+e'_{\pi}A\right][I-\gamma A]^{-1}$. Thus, (8) is equivalent to (15), given the VAR process.

Finally, we can directly use (22) to derive (14) because the second terms of the right hand side of (5) and (8) are the same.

References

Andrés, J., J. D. López-Salido, and E. Nelson, 2005, "Sticky Price Models and the Natural Rate of Hypothesis," *Journal of Monetary Economics*, 52(5), 1025–1053.

Calvo, G., 1983, "Staggered Prices in a Utility Maximizing Framework," *Journal of Monetary Economics*, 12(3), 383–398.

Carroll, C. D., 2003, "Macroeconomic Expectations of Households and Professional Forecasters," *Quarterly Journal of Economics*, 118(1), 269–298.

Christiano, L. J., M. Eichenbaum, and C. L. Evans, 2005, "Nominal Rigidities and the Dynamic Effect of a Shock to Monetary Policy," *Journal of Political Economy*, 113(1), 1–45.

Erceg, C. J., D. W. Henderson, and A. T. Levin, 2000, "Optimal Monetary Policy with Staggered Wage and Price Contracts," *Journal of Monetary Economics*, 46(2), 281–313.

Estrella, A., and J. C. Fuhrer, 2002, "Dynamic Inconsistencies: Counterfactual Implications of a Class of Rational-Expectations Model," *American Economic Review*, 92(4), 1013–1028.

Fischer, S., 1977, "Long-term Contracts, Rational Expectations and the Optimal Money Supply Rule," *Journal of Political Economy*, 85(1), 191–205.

Fuhrer, J., and G. Moore, 1995, "Inflation Persistence," *Quarterly Journal of Economics*, 110(1), 127–159.

Gali, J., 1992, "How Well Does the IS-LM Model Fit Postwar U.S. Data?," *Quarterly Journal of Economics*, 107(2), 709–738.

Gali, J., and M. Gertler, 1999, "Inflation Dynamics: A Structural Econometric Analysis," *Journal of Monetary Economics*, 44(2), 195–222.

Gertler, J. G. M., and J. D. López-Salido, 2005, "Robustness of the Estimates of the Hybrid New Keynesian Phillips Curve," *Journal of Monetary Economics*, 52(6), 1107–1118.

Kahn, H., and Z. Zhu, 2006, "Estimates of the Sticky-Information Phillips Curve for the United States," *Journal of Money, Credit and Banking*, 38(1), 195–208.

Kiley, M. T., 2005, "A Quantitative Comparison of Sticky-Price and Sticky-Information Models of Price Setting," unpublished paper.

Korenok, O., 2005, "Empirical Comparison of Sticky Price and Sticky Information Models," unpublished paper.

MacKinnon, J. G., 2002, "Bootstrap Inference in Econometrics," *Canadian Journal of Economics*, 35(4), 615–645.

Mankiw, G. N., 2001, "The Inexorable and Mysterious Tradeoff between Inflation and Unemployment," *Economic Journal*, 111, C45–C61.

Mankiw, N. G., and R. Reis, 2002, "Sticky Information Versus Sticky Prices: A Proposal to Replace the New Keynesian Phillips Curve," *Quarterly Journal of Economics*, 117(4), 1295–1328.

Mankiw, N. G., R. Reis, and J. Wolfers, 2003, "Disagreement about Inflation Expectations," in *NBER Macroeconomic Annual*, ed. by M. Gertler, and K. Rogoff. MIT Press, pp. 209–248.

Reis, R., 2005, "Inattentive Producers," NBER Working Paper No. 11820, forthcoming in *Review of Economic Studies.*

Rotemberg, J. J., 1982, "Sticky Prices in the United States," *Journal of Political Economy*, 90(6), 1187–1211.

Rotemberg, J. J., and M. Woodford, 1997, "An Optimization-Based Econometric Framework for the Evaluation of Monetary Policy," *NBER Macroeconomics Annual*, 12, 297–346.

Ruud, J., and K. Whelan, 2005a, "Does Labor's Share Drive Inflation?," *Journal of Money, Credit and Banking*, 37(2), 297–312.

Ruud, J., and K. Whelan, 2005b, "Modelling Inflation Dynamics: A Critical Survey of Recent Research," unpublished paper.

Ruud, J., and K. Whelan, 2006, "Can Rational Expectations Sticky-Price Models Explain Inflation Dyanmics," *American Economic Review*, 96(1), 303–320.

Sbordone, A. M., 2002, "Price and Unit Labor Costs: A New Test of Price Stickiness," *Journal of Monetary Economics*, 49(2), 265–292.

Sbordone, A. M., 2005, "Do Expected Future Marginal Costs Drive Inflation Dynamics?," *Journal of Monetary Economics*, 52(6), 1183–1197.

Stock, J. H., and M. W. Watson, 2001, "Vector Autoregressions," *Journal of Economic Perspective*, 15(4), 101–115.

Taylor, J. B., 1980, "Aggregate Dynamics and Staggered Contracts," *Journal of Political Economy*, 88(1), 1–23.

Woodford, M., 2001, "The Taylor Rule and Optimal Monetary Policy," *American Economic Review*, 91(2), 232–237.

Woodford, M., 2002, "Imperfect Common Knowledge and the Effect of Monetary Policy," in *Knowledge, Information, and Expectations in Modern Macroeconomics: In Honor of Edmund S. Phelps*, ed. by P. Aghion, R. Frydman, J. Stiglitz, and M. Woodford. Princeton University Press.