

Reference Prices, Costs, and Nominal Rigidities

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We assess the importance of nominal rigidities using a new weekly scanner dataset. We find that nominal rigidities take the form of inertia in reference prices and costs, defined as the most common prices and costs within a given quarter. Reference prices are particularly inertial and have an average duration of roughly one year, even though weekly prices change roughly once every two weeks. We document the relation between prices and costs and find sharp evidence of state dependence in prices. We use a simple model to argue that reference prices and costs are useful statistics for macroeconomic analysis. (JEL L11, L25, L81)

A central question in macroeconomics is whether nominal rigidities are important. In addressing this question the literature generally assumes that these rigidities take the form of sticky prices, i.e., prices that do not respond quickly to shocks. An important new literature discussed below assesses the importance of nominal rigidities by measuring how often prices change. In this paper we argue that nominal rigidities are important, but they do not necessarily take the form of sticky prices or, for that matter, sticky costs. Instead, they take the form of inertia in “reference prices” and “reference costs.” By reference price (cost) we mean the most often quoted price (cost) within a given time period, say a quarter.¹ In our dataset prices and costs change very frequently: the median duration is only three weeks for prices and two weeks for costs. However, the duration of reference prices is almost one year, while the duration of reference costs is almost two quarters. So both reference prices and reference costs are much more inertial than weekly prices and weekly costs.

What determines the duration of reference prices? Our analysis focuses on the relation between prices and costs paying particular attention to their reference values. We rely on a unique dataset that consists of weekly observations on price and cost measures for each item sold by a major US retailer in over 1,000 stores. We

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¹The existence of reference prices has been noted by various authors in the industrial organization literature (see, for example Elizabeth J. Warner and Robert B. Barsky 1995; Margaret E. Slade 1998; Kenn Ariga, Kenji Matsui, and Makoto Watanabe 2001; Martin Pesendorfer 2002; Daniel Hosken and David Reiffen 2004; and Pinelopi K. Goldberg and Rebecca Hellerstein 2008). With the exception of Goldberg and Hellerstein (2008) who use the Dominick’s data on the cost of beer, the other papers do not have data on cost.

find that prices are systematically but imperfectly related to costs. Strikingly, prices rarely change unless there is a change in cost. However, prices do not always change when costs change, so there is substantial variation in realized markups.

Our analysis suggests that the retailer chooses the duration of reference prices so as to limit markup variation. We base this inference on three findings. First, in over 90 percent of the observations the realized weekly markup is between plus and minus 10 percent of the average markup.² Significantly, this pattern holds for groups of goods with different reference price durations. Second, there is sharp evidence of state dependence in the probability of reference price changes. The probability of a reference price change is increasing in the difference between the markup that would obtain if the price did not change and the average value of the markup. Third, when the retailer changes reference prices it reestablishes the value of the unconditional markup, i.e., the retailer passes through all the changes in reference costs that have occurred since the last reference price change. Taken together, these findings support the view that the retailer chooses the duration of reference prices to keep markups within relatively narrow bounds.

We argue that our evidence is inconsistent with the three most widely used pricing models in macroeconomics: flexible-price models, standard menu-cost models, and Calvo-style pricing models. There is, however, a simple pricing rule that is consistent with our evidence. This rule can be described as follows. Prices do not generally change unless costs change. The unconditional markup and the duration of the reference price is good specific. For any given good the nominal reference price is on average a particular markup over nominal reference cost. The retailer resets the reference price so as to keep the actual markup within plus/minus 10 percent of the desired markup over reference cost. On average when the retailer changes the reference price it reestablishes the unconditional markup. With this rule reference prices can exhibit substantial nominal rigidities even though weekly prices change frequently.

Our results raise an obvious question: why should a macroeconomist care about reference prices and costs? One possibility is that macroeconomists can safely abstract from high-frequency movements in prices and costs when analyzing the nature of the monetary transmission mechanism. From this perspective, significant persistence in reference prices and costs are a manifestation of a type of rigidity not present in conventional macro models. Another possibility is that high-frequency movements in prices and cost are important for understanding the monetary transmission mechanism.

To explore these issues we develop a simple partial-equilibrium model which captures key features of the data that we document in our empirical work. In our setup the firm chooses a “price plan” which consists of a small set of prices. The firm can move between prices in this set without incurring any cost. However, there is a fixed cost of changing the price plan. The model is calibrated so that, among other things, it is consistent with the observed duration of weekly and reference price changes. We mimic the effect of a monetary policy shock by considering a shock that, absent pricing frictions, would have no effect on quantities. In the presence of sticky plans a monetary policy shock has a large effect on quantities and very little effect on

² Our agreement with the retailer does not permit us to report information about the level of the markup for any one item or group of items.

prices. So, monetary policy has important real effects in our model even though prices change frequently.

Taking our model as the true data-generating process we proceed in the spirit of Patrick Kehoe and Virgiliu Midrigan (2007) and address the question: do simpler models provide a good approximation to the real effects of monetary policy? We focus attention on two calibrations of the standard menu-cost model. In the first calibration we choose the menu cost so that the model matches the frequency of observed weekly price changes. As a result, prices are quite flexible and the model generates the misleading conclusion that a monetary policy shock has a very small effect on the level of economic activity. In the second calibration we choose the menu cost so that the model reproduces the observed frequency of reference price changes. As a result, prices are quite sticky and the model does a very good job of reproducing the real effects of a monetary policy shock. These results suggest that the frequency of reference price changes is more revealing about the underlying nature of nominal rigidities than the simple frequency with which prices and costs change.

Our paper is related to the recent literature which uses micro datasets to measure the frequency of price changes. The seminal article by Mark Bils and Peter Klenow (2004) argues that prices are quite flexible. Using monthly consumer price index (CPI) data, they find that median duration of prices is 4.3 months. This estimate has become a litmus test for the plausibility of monetary models.³ In contrast, Emi Nakamura and Jón Steinsson (2007) focus on nonsale prices and argue that these prices are quite inertial. When sales are excluded, prices change on average every eight to 11 months. Kehoe and Midrigan (2007) also examine the impact of sales on price inertia. They use an algorithm to define sale prices that they apply to weekly supermarket scanner data. They find that, when sales observations are excluded, prices change once every 4.5 months. When sales are included, prices change every three weeks. Excluding “sale prices” from the data has a major impact on inference about price inertia. Not surprisingly, there is an ongoing debate in the literature about how to define a sale and whether one should treat “regular” and “sale” prices asymmetrically. An advantage of working with reference prices is that we do not need to take a stand on what sales are or whether they are special events that should be disregarded by macroeconomists.

This paper is organized as follows. Section I describes our data and discusses the relation between our measure of cost and marginal cost. In Section II we compare the behavior of weekly prices and reference prices. In Section III we contrast the behavior of weekly costs and reference costs. In Section IV we examine the relation between cost and price changes. In Section V we document additional features of the data that are useful for evaluating the plausibility of different pricing models. In Section VI we discuss the implications of our empirical findings for various price-setting models. In Section VII we present a simple sticky-plan model which we use to discuss the relevance of reference prices and costs. Section VIII concludes.

³ See, for example, David Altig et al. (forthcoming), and Mikhail Golosov and Robert E. Lucas Jr. (2007).

I. Data

Our analysis is primarily based on scanner data from a large food and drug retailer that operates more than 1,000 stores in different US states. The sample period is 2004 to 2006. We have observations on weekly quantities and sales revenue for roughly 60,000 items in each of the retailer's stores. By an item we mean a good, as defined by its universal product code (UPC), in a particular store. We include only items that are in the dataset for a minimum of 12 weeks in every quarter of the entire three-year period. This requirement reduces our sample to 243 stores and 405,000 UPC-store pairs. Most of the items in our dataset are in the processed food, unprocessed food, household furnishings, and "other goods" categories of the CPI.⁴ The retailer classifies items as belonging to one of 200 categories (e.g., cold cereal), and we use the retailer's category classification in our analysis.

We use our data on sales revenue and quantities sold to compute the price for each individual item. The retailer adjusts prices on a weekly basis, so daily movements in prices are not a source of measurement error in our weekly prices measures. Despite the high quality of scanner data there are several potential sources of measurement error associated with our price measure. First, some items are sold at a discount to customers who have a loyalty card. Second, some items are discounted with coupons. Third, there are two, or more, for one promotions. If there are changes over time in the fraction of customers who take advantage of these types of discounts, then our procedure for computing prices would induce spurious price changes. For these reasons, our estimates of the duration of weekly and reference prices provide lower bounds on the true duration statistics.

We construct a weekly measure of the retailer's cost for each item in each store, using data on sales and adjusted gross profit. The latter is defined as

$$\text{Adjusted gross profit} = \text{Sales} - \text{Cost of goods.}$$

The cost of goods is the vendor cost net of discounts and inclusive of shipping costs. This measure is the most comprehensive cost measure available to us. This cost measure is viewed by the retailer as measuring the replacement cost of an item, and it is the cost measure they use in their pricing decisions.

The relation between our cost measure and marginal cost depends on the nature of the retailer's production function. Suppose, for example, that to sell one unit of an item, the retailer must have one unit of that item and one unit of a composite factor produced using labor and capital. We denote by L the number of units of the composite factor and by w the price of this factor. The wholesale price of the item is given by c . We assume that in the short run L is predetermined. Suppose that the cost of selling Y units of the item is given by:

$$C(Y) = \begin{cases} wL + cY & \text{if } Y \leq L, \\ wL + cL + \psi(Y - L) & \text{if } Y > L. \end{cases}$$

⁴ Examples of items in the "other goods" category include laundry detergents, flowers, and magazines.

The firm chooses a scale of operation which is summarized by its choice of L . At any point in time, the number of customers entering the store, Y , need not equal L . When Y is greater than L the cost of providing the extra $Y - L$ goods is ψ . We assume that $\psi > w + c$. We can interpret $\psi - (w + c)$ as the implicit cost of a stockout, or the cost of meeting unusually high demand, say by hiring overtime labor and obtaining rush orders from the wholesaler. Nothing of importance that follows depends on this admittedly simplistic model of the cost of meeting unusually high demand.

The retailer chooses L to minimize the expected cost of selling Y units:

$$\begin{aligned} \min_L E[C(Y)] &= \int_0^L (wL + cY) f(Y) dY \\ &+ \int_L^\infty [wL + cL + \psi(Y - L)] f(Y) dY, \end{aligned}$$

where $f(Y)$ is the probability density function of Y . Here we make the simplifying assumption that c is known when L is chosen. The optimal value, L^* , satisfies

$$F(L^*) = 1 - \frac{w}{\psi - c},$$

where $F(\cdot)$ denotes the cumulative density function of Y . Realized total cost is given by

$$C(Y) = \begin{cases} wL^* + cY & \text{if } Y \leq L^*, \\ (w + c)L^* + \psi(Y - L^*) & \text{if } Y > L^*. \end{cases}$$

As long as $Y \leq L^*$, marginal cost is given by c , and our cost measure is a very good proxy for marginal cost. When $Y > L^*$ our cost measure understates actual marginal cost.

There are other production functions for which our cost measure may not correspond closely to marginal cost. For example, suppose that retail output, Y , is given by

$$Y = AL^{1-\alpha} Q^\alpha,$$

where Q is the number of items purchased by the retailer from the wholesaler. The cost of each item is given by c . As above, suppose that L is predetermined but optimally chosen. Then, short-run marginal cost is given by

$$C'(Y) = \frac{w^{1-\alpha} c^\alpha Y^{(1-\alpha)/\alpha}}{\alpha^\alpha (1 - \alpha)^{1-\alpha} A \left[\int_0^\infty (Y^{1/\alpha}) f(Y) dY \right]^{1-\alpha}}.$$

Note that, absent uncertainty, marginal cost is constant.⁵ The presence of uncertainty makes marginal cost an increasing function of output. As α goes to one, short-run marginal cost approaches c . So, the higher α is the better our cost measure is

⁵ In this case, $C'(Y) = w^{1-\alpha} c^\alpha / [A \alpha^\alpha (1 - \alpha)^{1-\alpha}]$.

as a proxy for marginal cost. In the remainder of the paper we proceed under the assumption that our cost measure is a reasonable proxy for marginal cost.

As a robustness check we use a second dataset obtained from Dominick's, a chain of grocery stores in the Midwest with 100 outlets. This dataset has been used in a variety of other studies (e.g., Judith Chevalier, Anil K. Kashyap, and Peter E. Rossi 2003 and Virgiliu Midrigan 2006). The Dominick's dataset includes weekly observations on price and sales revenue for 3,500 items over the period 1989–1997. This set includes a cost measure. However, this measure does not correspond to the replacement cost or the last wholesale price at which Dominick's bought the item, but rather the average acquisition cost of the items in inventory. Consequently, we do not use this cost measure.

Our scanner data has advantages and disadvantages relative to the CPI data used by authors such as Bils and Klenow (2004) and Nakamura and Steinsson (2007). A disadvantage is that our datasets do not cover all of the goods in the CPI. However, the median frequency of price change is the same for the items in our datasets and the CPI basket. In this sense, the items in our dataset are not unrepresentative of those in the CPI basket. An important advantage of our scanner data is that it is available at a weekly frequency and includes information about quantities and costs, as well as prices.

Given the large number of items in our dataset we must adopt a procedure to parsimoniously report our findings. Unless stated otherwise, the statistics that we report are computed as follows. First, we calculate the median value of a statistic across all items in a given category. We then compute the median of the 200 category medians. As a robustness check we also report results for revenue-weighted medians across categories.

II. The Behavior of Weekly Prices and Reference Prices

In this section we compare the behavior of weekly and reference prices. Recall that the reference price of an item is the most commonly observed price for that item within a quarter. We refer to all other prices as nonreference prices. Our basic findings in this section are twofold. First, according to various metrics reference prices are important. Second, reference prices are much more persistent than weekly prices.

A. Reference Prices

Within a given quarter, weekly prices typically fluctuate between reference and nonreference prices. To summarize these within-quarter fluctuations we estimate a two-state Markov chain. In state one the weekly price is equal to the reference price. In state two the weekly price is different from the reference price. The average estimated Markov chain across categories is given by:⁶

$$(1) \quad M_p = \begin{bmatrix} 0.74 & 0.26 \\ 0.31 & 0.69 \end{bmatrix}.$$

⁶ We estimate the transition matrix for the Markov chain for each item in every quarter in our sample and take the average over all quarters. We then compute the average transition matrix for items within a category. Finally, we compute the average transition matrix across categories.

TABLE 1—BASIC STATISTICS

Basic statistics	Primary dataset	Dominick's dataset
Fraction of weeks spent at the reference price	0.62	0.77
Fraction of weeks spent at the reference cost	0.54	NA
Fraction of quarters in which weekly prices are constant for the whole quarter	0.11	0.19
Fraction of quarters in which weekly cost is constant for the whole quarter	0.06	NA
Fraction of nonreference prices that are above reference prices ^a	0.21	0.30
Fraction of price changes that are from a nonreference price to a reference price	0.29	0.41
Fraction of cost changes that are from a nonreference cost to a reference cost	0.25	NA
Fraction of quantities sold at reference prices	0.49	0.66
Fraction of revenue collected at reference prices	0.54	0.68
Probability of weekly price changing when weekly cost does not change	0.03	NA
Probability of reference price changing when reference cost does not change	0.15	NA

^a Computed out of the total weeks in which the weekly price is different from the reference price.

It is evident from M_p that, for most weeks in a given quarter, the weekly price coincides with the reference price. Interestingly, the matrix M_p is consistent with the notion that weekly prices have “memory.” When prices move away from their reference value they have a tendency to return to that value. In particular, nonreference prices return to a given reference price with 31 percent probability.

The matrix M_p pertains to within-quarter price fluctuations. We now quantify the importance of reference prices using statistics calculated across quarters. Unless otherwise indicated these statistics are reported in Table 1. First, 29 percent of all price changes involve movements from a nonreference price to a reference price. Second, the weekly price is equal to the reference price in 62 percent of the weeks. Third, half of the total quantities sold are sold at reference prices. Fourth, 54 percent of the revenue is collected at reference prices. Fifth, the standard deviation of quantities sold at reference prices is roughly the same as the standard deviation of quantities sold at nonreference prices (42 versus 43 percent, see Table 2). The first three observations imply that prices are often equal to reference prices and price movements are often movements toward reference prices. The last two observations imply that reference prices are important in terms of the level and volatility of quantities sold.

There is substantial heterogeneity in the importance of reference prices across categories. To illustrate this point Figure 1 displays the distribution of weeks spent and quantities sold at the reference price.⁷ For more than 75 percent of the categories the price of the median item within a category is equal to the reference price more than 50 percent of the time. However, there are some extreme outlier categories. For maga-

⁷ Recall that for a given item in a given quarter to be included in the dataset we require that there be either 12 or 13 weeks of observations for that item and for that quarter. This rule implies that there are only 24 possible values (1/12, 2/12, ..., 12/12, 1/13, 2/13, ..., 12/13) for the percentage of weeks spent at the reference price.

TABLE 2—VOLATILITY PROPERTIES

	Primary dataset	Dominick's dataset
<i>Standard deviation of levels</i>		
Standard deviation of quantities		
Log(weekly quantity)	0.53	0.67
Log(quantities sold at reference price)	0.42	0.41
Log(quantities sold at nonreference prices)	0.43	0.42
Standard deviation of prices		
Log(weekly price)	0.14	0.11
Log(reference price)	0.08	0.07
Log(weekly price), conditional on weekly price change	0.15	0.15
Log(reference price), conditional on reference price change	0.10	0.07
Standard deviation of costs		
Log(weekly cost)	0.12	NA
Log(reference cost)	0.07	NA
Log(weekly cost), conditional on cost change	0.13	NA
Log(reference cost), conditional on cost change	0.08	NA
Standard deviation of prices/standard deviation of costs ^a		
Weekly prices/weekly costs	1.08	NA
Reference prices/reference costs	1.15	NA
Weekly prices, conditional on price changes/weekly cost conditional on cost change	1.08	NA
Reference price, conditional on price changes/reference cost, conditional on cost change	1.17	NA
Standard deviation of markup		
Log(weekly markup)	0.11	NA
Log(reference markup)	0.09	NA
<i>Standard deviation of changes</i>		
Standard deviation of prices		
Log changes in weekly prices	0.14	0.09
Log changes in reference prices	0.08	0.04
Log changes in weekly prices, conditional on price change	0.20	0.19
Log changes in reference prices, conditional on price change	0.14	0.07
Standard deviation of costs		
Log changes in weekly cost	0.11	NA
Log changes in reference cost	0.06	NA
Log changes in weekly cost, conditional on cost change	0.15	NA
Log changes in reference cost, conditional on cost change	0.09	NA
Standard deviation of prices/standard deviation of costs ^a		
Weekly growth rate of prices/weekly growth rate of costs	1.10	NA
Reference growth rate of prices/growth rate of costs	1.13	NA
Weekly growth rate of price, conditional on price change/weekly growth rate of cost, conditional on cost change	1.20	NA
Growth rate of reference prices conditional on price change/growth rate of reference costs, conditional on cost change	1.25	NA

^a The median of the ratio of standard deviations is not the ratio of the median standard deviations.

zines the price never changes in our sample. In contrast, for the categories grapes, bananas, and pears the weekly price coincides with the reference price only 8 percent of the time. The right panel of Figure 1 shows that, for 70 percent of the categories, the quantity of the median item sold at the reference price is above 40 percent of total sales. Again, magazines, bananas, and pears are outlier categories.

Throughout this paper we calculate the reference price of an item as the most common price for that item within a quarter. We choose the quarter as the unit of time since

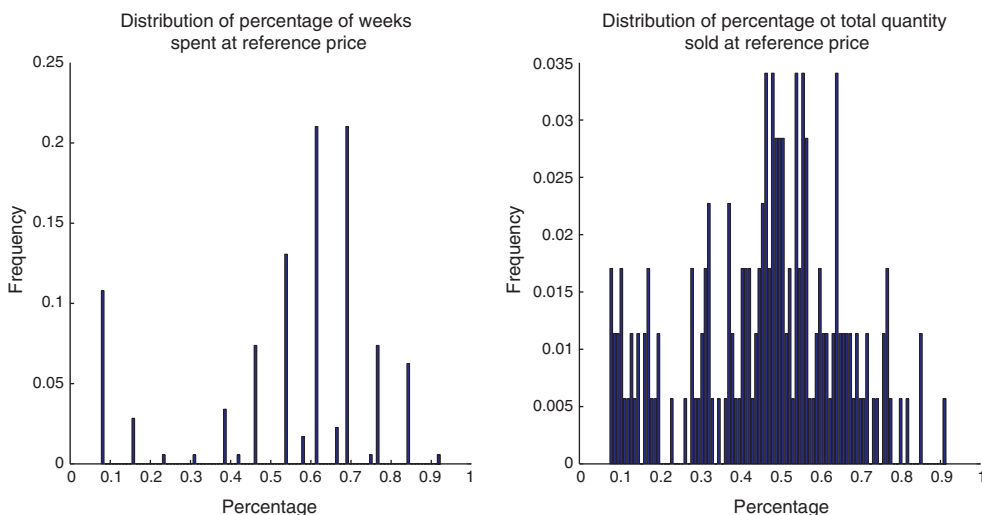


FIGURE 1

most quantitative macro models use quarterly data. However, the basic reference phenomenon emerges even when we define reference prices as the most common price in a month. During the 36 months included in our sample 42 percent of the monthly reference prices are identical. So, even at the monthly frequency, there is a reference price that serves as an attractor around which weekly prices fluctuate.

B. Price Persistence

We now contrast the persistence properties of weekly prices and reference prices. According to Table 3 the probability of a weekly price change is 0.43. The implied duration of a weekly price is 2.3 weeks or 0.18 of a quarter.⁸ The top panel of Figure 2 displays the distribution of the duration of weekly prices across categories.⁹ Clearly, weekly prices are not sticky.

In sharp contrast to weekly prices, the probability of a reference price change is 0.27. So, the implied duration of reference prices is roughly 3.7 quarters (see Table 3).¹⁰ The bottom panel of Figure 2 displays the distribution of the duration of reference prices across categories.¹¹ This figure shows that 80 percent of the categories have reference price duration greater than 20 weeks. Clearly, there is

⁸ To facilitate comparisons with other estimates in the literature we calculate duration as the inverse of the frequency of price change. A shortcoming of this calculation is that it abstracts from the bias associated with Jensen's inequality (see Jeffrey Campbell and Benjamin Eden 2005 for a discussion).

⁹ Since magazine prices never change in our sample, they have an infinite weekly price duration. For this reason we excluded magazines from Figure 2.

¹⁰ Intriguingly, this duration roughly coincides with the modal response that Alan Blinder et al. (1998) obtained when they asked firms: how often does the price of your most important product change in a given year?

¹¹ Recall that for an item to be included in our dataset we require that there be 12 quarters of data for this item. This rule implies that there are only 11 possible values for the frequency of reference price changes. The number of reference price changes can be equal to 1, 2, ..., 11. Consequently there are 12 possible values for the quarterly frequency of reference price change, 0, 1/11, 2/11, ..., 11/11. There are also 12 possible values for the duration of reference prices: ∞ , 11, 11/2, 11/3, ..., 1. In Figure 2 these quarterly durations are multiplied by 13 to convert them to weekly durations.

TABLE 3—PERSISTENCE PROPERTIES

	Primary dataset	Dominick's dataset
Price persistence		
Probability of a weekly price change	0.43	0.24
Implied weekly price duration in quarters	0.18	0.32
Probability of reference price change	0.27	0.33
Implied reference price duration (in quarters)	3.70	3.03
Cost persistence		
Probability of weekly cost change	0.49	NA
Implied weekly cost duration (in quarters)	0.16	NA
Probability of reference cost changes	0.45	NA
Implied reference cost duration (in quarters)	2.22	NA

substantial inertia in reference prices. These prices exhibit nominal rigidities that are not revealed by studying weekly prices.

One might be concerned that reference prices just correspond to “sticky prices.” For example, if prices were literally constant, a reference price would account for 100 percent of the price observations. In fact, reference prices do not necessarily correspond to “sticky prices.” The median percentage of quarters across categories in which weekly prices are constant for an entire quarter is only 10 percent. In fact, reference prices are quite volatile. According to Table 2 reference prices are roughly 60 percent as volatile as weekly prices. This result is robust to whether we work with log levels or growth rates.¹²

C. Nonreference Prices and Sales Prices

Nonreference prices do not necessarily correspond to “sale prices.” In fact, 21 percent of nonreference prices in our sample are actually *higher* than the corresponding reference price (see Table 1).

In principle, the finding that many nonreference prices are higher than reference prices could be spurious for the following reason. Our procedure for defining a reference price assumes that the firm makes decisions on a quarterly basis. This assumption might be incorrect. Suppose that the retailer increases the actual reference price toward the end of a given quarter. Our procedure would classify those prices as nonreference prices that are higher than the reference price. Similarly, suppose the retailer lowers the reference price near the beginning of the quarter. Our procedure would classify the actual old reference prices that occur in the beginning of the quarter as higher than the measured reference price for that quarter.

To produce an upper bound on the quantitative importance of these two scenarios we compute the fraction of the high nonreference prices that are not equal to the reference price in the previous or subsequent quarter. We find that this fraction is equal to 60 percent. So, a lower bound for the fraction of nonreference prices that are actually higher than the corresponding reference price is 12 percent (0.21 times 0.60). Taken as a whole our results indicate that nonreference prices are not necessarily “sale prices.”

¹² We obtain a similar finding for the relative volatility of new weekly prices and new reference prices (see Table 2).

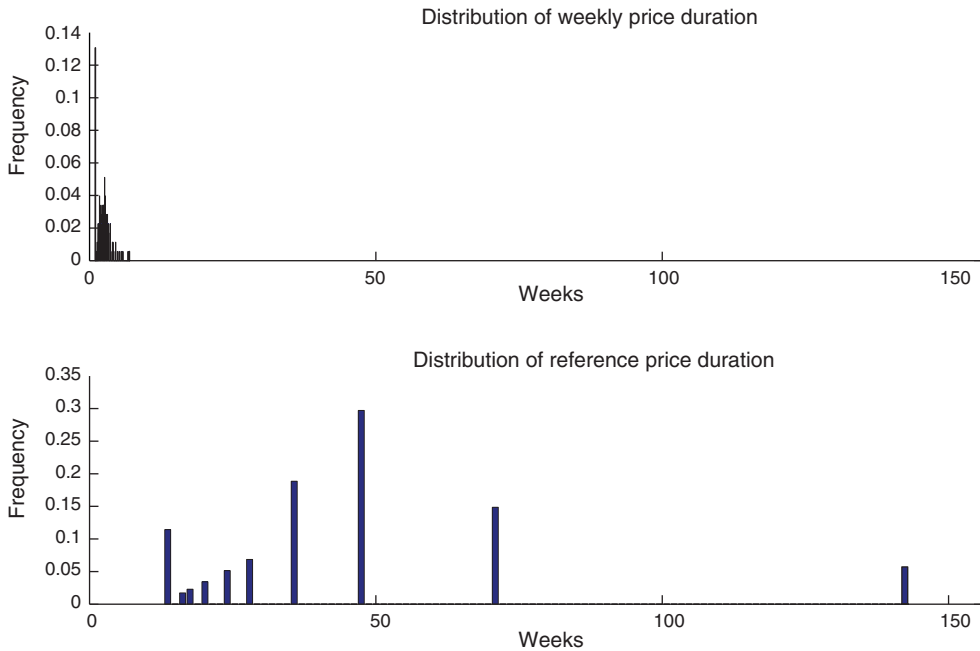


FIGURE 2

An alternative scenario is that the actual reference price changes in the middle of the quarter, and the retailer puts the item on sale before the end of the quarter. In this scenario we might spuriously classify the sale price as being above the reference price.¹³ To assess the robustness of our basic finding regarding high nonreference prices to this type of scenario we implemented the following algorithm.¹⁴

Step 1: Find the reference price for a given quarter, P_t , as the mode of the weekly prices for that quarter. Denote by t' and t'' the first and last time that we observe P_t within the quarter, respectively.

Step 2: Find the last week, $t^* < t'$, within a quarter in which the weekly price equals last quarter's reference price, P_{t-1} . The reference price up to time t^* is P_{t-1} . If there is no $t^* < t'$ or t^* does not exist the reference price is equal to P_t .

Step 3: Find the first week, $t^{**} > t''$, within a quarter in which the weekly price equals next quarter's reference price, P_{t+1} . The reference price is P_{t+1} from t^{**} to the end of the quarter. If there is no $t^{**} > t''$ or t^{**} does not exist the reference price is equal to P_t .

Step 4: Find the fraction of weeks in which the price is above the newly computed reference prices.

¹³ For concreteness, consider the following price sequence in which the actual reference price changes from 5 to 7 in the middle of the quarter: 5, 5, 5, 5, 5, 5, 5, 5, 7, 7, 7, 7, 6, 7, 7, 7. Note that 6 is a sale price relative to 7. Our previous robustness procedure would eliminate the 7s as observations for which the nonreference price is above the reference price. But that procedure would not eliminate 6 as such an observation.

¹⁴ We thank an anonymous referee for suggesting this algorithm.

Implementing this algorithm we find that the fraction of high nonreference prices falls from 21 percent to 15 percent.

We understand that our robustness checks may not necessarily eliminate all nonreference prices that are spuriously classified as high. Still, we believe that, taken as a whole, our results support the view that nonreference prices are not necessarily “sale prices.”

D. *Some Robustness Checks*

As discussed above there can be spurious changes in prices in our dataset associated with the time-varying use of loyalty cards, coupons, and promotions. Consequently, our estimate of the duration of weekly prices (0.18 of a quarter) is a lower bound on the true duration of weekly prices. From this perspective prices could be more inertial than suggested by our point estimates. We use two approaches to assess the potential impact of measurement error on our duration estimates.

First, we recompute the probability of a price change assuming that an actual price change occurs only when our price measure changes by more than x percent, for $x = 1, 2, \dots, 5$. Weekly price duration is an increasing function of x and peaks at 0.27 of a quarter when $x = 5$ (recall that our benchmark value of weekly price duration is 0.18 of a quarter). Significantly, the reference price duration remains equal to our benchmark estimate of 3.7 quarters for all the values of x that we consider. So, the basic finding that reference prices are much more persistent than weekly prices is unaffected by this type of measurement error.

Second, we use an additional dataset from the retailer that contains the actual price associated with each transaction for 374 stores in Arizona, California, Colorado, Oregon, Washington, and Wyoming. Because prices are observed directly, there is no measurement error associated with the time-varying use of discounts, coupons, loyalty cards, and other promotions. This dataset is available only for a short time period (January 4 to December 31, 2004). The average number of days in which we observe the same item is 14. So, while we cannot use this dataset to compute price duration, we can use it to quantify the bias introduced by the use of unit-value prices.

For the new dataset we identify all UPCs that are sold three or more times in the same store in the same day and are included in the data for at least seven days. There are 1.7 million such observations. In 70 percent of these observations the same good is sold at the same price in all transactions that occur in the same store and on the same day. So, in this dataset, measurement error can at most affect 30 percent of the observations. We can use this statistic to quantify the impact of measurement error on the duration of weekly prices. The probability of a weekly price change is 0.41. Suppose that 30 percent of these changes are indeed spurious. Then, the true probability of a weekly price change is $0.7 \times 0.41 = 0.29$. This probability of a weekly price change implies a duration of weekly prices of 0.27 quarters. Interestingly, this estimate coincides with the one we obtained using our first method for assessing the importance of measurement error.

This new dataset is not long enough to allow us to compute reference prices. But any correction for measurement error would only increase the duration of reference prices. So, by correcting the duration of weekly prices but not the duration of reference prices we are providing a conservative estimate of the difference between

the two. This estimate is 3.43 quarters ($3.7 - 0.27$). We conclude that, even taking measurement error into account, the duration of reference prices is much longer than the duration of weekly prices.

Our main results pertain to statistics calculated using medians across categories. To assess the robustness of these results we also compute statistics using revenue-weighted medians across categories. We find that, with one possible exception, our results are robust to this alternative procedure. The one exception is that the point estimate of the duration of reference prices goes from 3.7 to 2.7 quarters. The duration of weekly prices is essentially unchanged. So, the basic qualitative result that reference prices are much more persistent than weekly prices is unaffected.

E. Results for Dominick's Dataset

We conclude this section by briefly discussing the results that we obtain with the Dominick's dataset. As tables 1 through 3 show, these results are very similar to those obtained with our primary dataset. Reference prices are important. First, weekly prices are often equal to reference prices (77 percent of the weeks). Second, price movements are often movements toward reference prices. The fraction of price changes that are from a nonreference price to a reference price is 41 percent. Third, reference prices continue to be important in terms of the fraction of quantities sold at reference prices (66 percent) and the volatility of quantities sold at reference prices (41 percent).

Finally, we find the same sharp contrast between the duration of weekly and reference prices. The duration of weekly prices is 0.32 quarters while the duration of reference prices is roughly three quarters.

III. The Behavior of Weekly Costs and Reference Costs

In this section we compare the behavior of weekly and reference costs. The latter is defined as the most commonly observed cost for that item within a quarter. We refer to all other costs as nonreference costs. Our basic findings in this section can be summarized as follows. First, judging by various measures, reference cost are important. Second, reference costs are much more persistent than weekly costs. Third, reference costs are less persistent than reference prices.

A. The Importance of Reference Costs

We summarize within-quarter fluctuations in costs using a two-state Markov chain with the following states. In state one the weekly cost is equal to the reference cost. In state two the weekly cost is different from the reference cost. The average Markov chain across categories is given by:

$$M_c = \begin{bmatrix} 0.70 & 0.30 \\ 0.25 & 0.75 \end{bmatrix}.$$

The estimated Markov chain for costs is quite similar to the analog Markov chain for prices. In most weeks in a given quarter, the weekly cost coincides with the reference cost. As with prices, nonreference costs often return to a given reference cost.

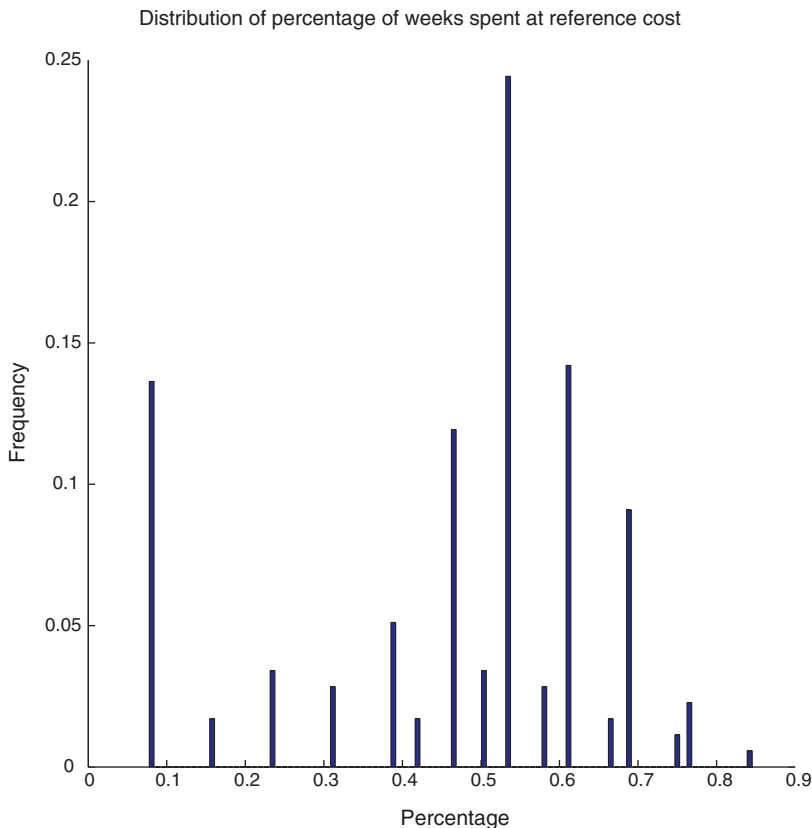


FIGURE 3

To quantify the importance of reference costs we use statistics calculated across quarters. First, 25 percent of all cost changes involve movements from a nonreference cost to a reference cost (see Table 1). Second, the weekly cost is equal to the reference cost in 54 percent of the weeks in our sample (see Table 1). As with prices, there is substantial heterogeneity in the importance of reference costs across categories. Figure 3 displays the distribution across categories of weeks in which the weekly cost is equal to the reference cost. There are some extreme outlier categories. For magazines the cost never changes in our sample. In contrast, for the categories grapes, bananas, and pears the weekly cost coincides with the reference cost only 8 percent of the time. Recall that these categories are also outliers in terms of the fraction of weeks in which the weekly price is equal to the reference price.

B. Cost Persistence

As with prices, there is a sharp contrast between the persistence properties of weekly costs and reference costs. From Table 3 we see that the probability of a weekly cost change is 0.49. So, the implied duration of a weekly cost is 0.16 of a quarter, or roughly 2.1 weeks. The top panel of Figure 4 displays the distribution of duration of weekly costs across categories. Clearly, weekly costs are not sticky.

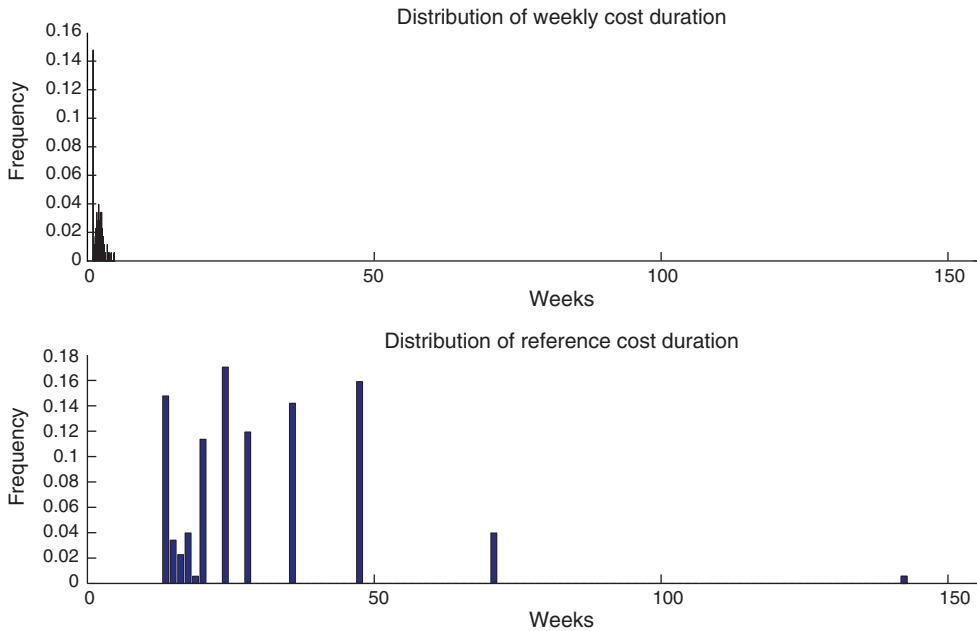


FIGURE 4

The probability of a reference cost change is 0.45. So, the implied duration of reference costs is roughly 2.2 quarters. The bottom panel of Figure 4 displays the distribution of reference cost duration across categories. Roughly two-thirds of the categories have reference cost duration exceeding 20 weeks. Clearly, there is substantial inertia in reference costs. The existence of stickiness in costs would not be revealed by analyzing weekly costs.

As with reference prices, one might be concerned that reference costs just correspond to sticky costs. This concern is not warranted. Across all categories, the median percentage of quarters in which weekly costs are constant is only 6 percent. In fact reference costs are quite volatile. According to Table 2 reference costs are roughly 60 percent as volatile as weekly costs.¹⁵

We conclude this section by noting that our weekly cost measures can have an endogenous component associated with trade promotions. As discussed in Laoura Maratou (2006) and Maratou, Miguel Gómez, and David Just (2004), there are basically two types of trade promotions: performance-based contracts and discount-based contracts. Performance-based contracts give retailers incentives to sell the manufacturer's product. These incentives are tied to a measure of retailer performance (e.g., units sold, displayed, or price discounts in effect during a given period). We think of these contracts as exogenous price schedules that are nonlinear in nature. The main impact of this nonlinearity is to potentially introduce measurement error into our analysis by driving a wedge between the retailer's average and marginal cost.

¹⁵ We obtain a similar finding for the relative volatility of new weekly costs and new reference costs (see Table 2).

Discount-based promotions can induce a different type of endogeneity. These promotions generally take the following form: suppliers provide merchandise to retailers at a discount, usually for a brief, specified period (two to three weeks is standard). Changes in cost and prices induced by these types of promotions are likely to be transitory in nature. For this reason they are unlikely to affect reference costs and prices, which have an average duration of six months and one year, respectively.

IV. The Determinants of Price Changes

In this section we investigate the relation between reference prices and costs and find that there is a very important form of state dependence in reference prices. Specifically, the duration of reference prices is chosen to limit markup variation. This finding is based on four observations that we document below. First, the duration of reference prices is such that the variation of markups within the spell of a reference price is within ± 10 percent of the average markup. Second, there is evidence of state dependence in the probability of reference price changes. Third, when the retailer changes reference prices it reestablishes the value of the unconditional markup. Finally, in periods in which the reference price is constant before it rises (falls), the markup falls (rises).

A. *The Relation between Prices and Cost Changes*

A striking property of our data is that prices generally do not change absent a change in costs. The probability that the weekly price changes without a change in the weekly cost is only 3 percent (see Table 1). The probability that the reference price changes without a change in reference cost is 15 percent.

We do not find an important lag or lead in the relation between changes in costs and changes in prices. We assess whether there is a lag in the response of prices to changes in cost by computing the probability of a price change at time $t + 1$, conditional on a cost change occurring at time t , no price change occurring at time t , and no cost change occurring at $t + 1$. This probability is 4 percent and 15 percent for weekly and reference prices, respectively. So, there does not seem to be an important lag in the response of prices to changes in costs.

To see if there is a lead in the response of prices to changes in cost we compute the probability of a price change at time $t - 1$, conditional on a cost change occurring at time t , no price change occurring at time t , and no cost change occurring at $t - 1$. This probability is 4 percent and 16 percent for weekly and reference prices, respectively. These results suggest that there are no important leads in the response of prices to changes in costs.

While prices generally do not change absent a change in costs, a change in cost is not sufficient to induce a change in price. This fact means that there are substantial variations in markups. According to Table 2 the standard deviation of the weekly markup is 11 percent. The standard deviation of the reference markup, defined as the standard deviation of the ratio of reference prices to reference costs, is 9 percent.

We now analyze deviations of the markup from its average value. To this end, we compute the percentage difference between the realized weekly markup and the

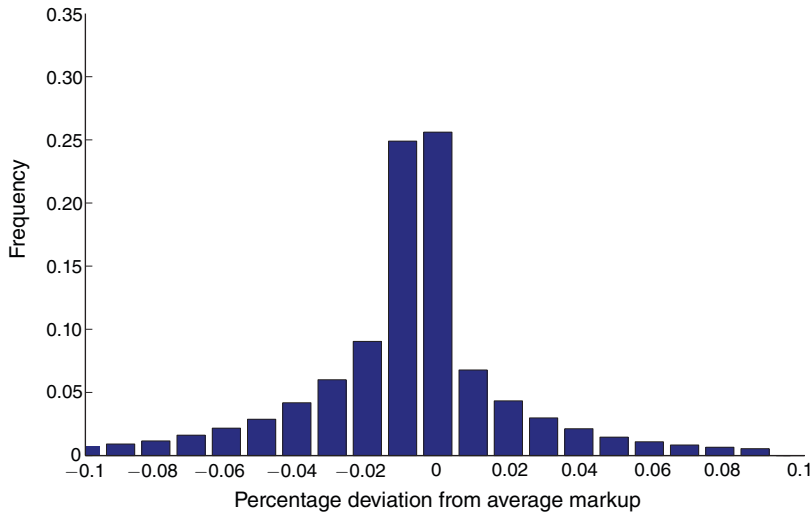


FIGURE 5

mean unconditional markup for weeks in which the weekly price coincides with the reference price. Figure 5 displays the distribution of this statistic. Interestingly, 90 percent of the probability mass is between plus and minus 10 percent of the average markup. This finding suggests that the retailer resets its reference prices so that variations in the realized markup fall within a reasonably small interval.

To assess this hypothesis, we compute the analog of Figure 5 for different categories of goods, classified according to the median duration of the reference price. The results are displayed in Figure 6 for groups of goods with median durations ranging from one to 12 quarters. These distributions are generally similar to those displayed in Figure 5. This finding is consistent with the hypothesis that the retailer chooses the duration of the reference price for each item to keep realized markups within similar small bounds. Figure 7 provides further evidence in support of this hypothesis. This figure shows that categories with a high probability of a reference cost change have a high probability of a reference price change.¹⁶

B. State Dependence in Reference Prices

A natural question to ask is whether there is any state dependence in the probability of reference price changes. To address this question, we define the “hypothetical reference markup” as the reference markup that would obtain if the retailer did not change its reference price between quarter $t - 1$ and quarter t . Thus, the hypothetical reference markup is the ratio of the reference price in quarter $t - 1$ to the reference cost in quarter t . The top panel of Figure 8 displays the median probability that the reference price changes as a function of the percentage deviation of the hypothetical reference markup from the average markup. The probability that the reference price changes when the hypothetical reference markup is equal to the

¹⁶ Recall that there are only 12 quarters in our sample, so the probability of a change in reference price or cost can take only a discrete number of values.

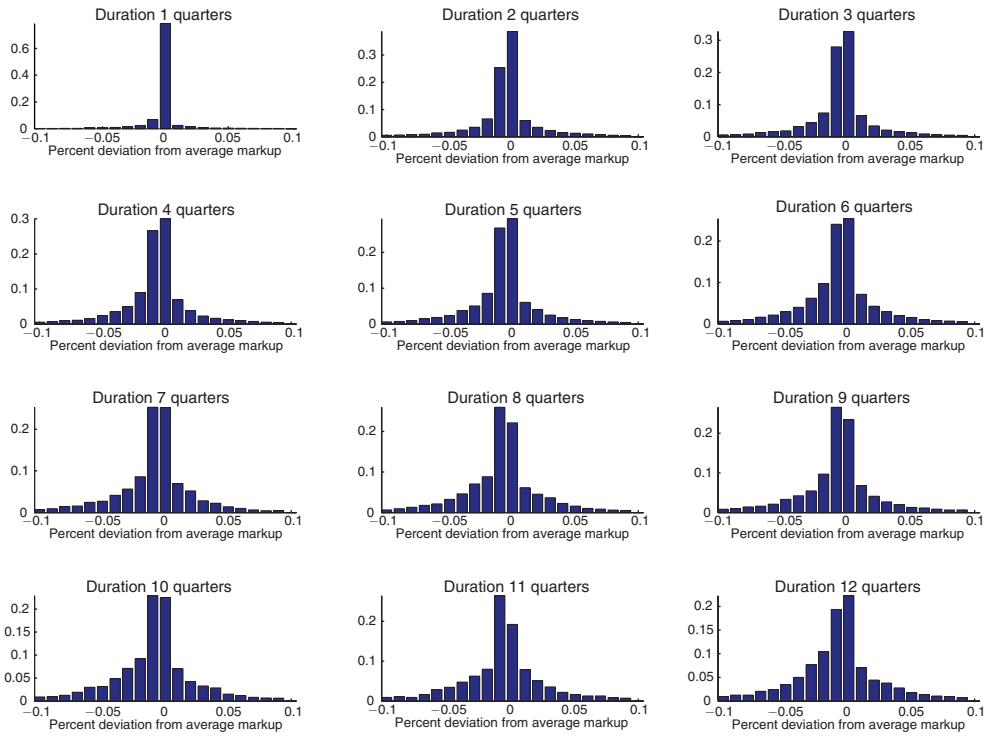


FIGURE 6

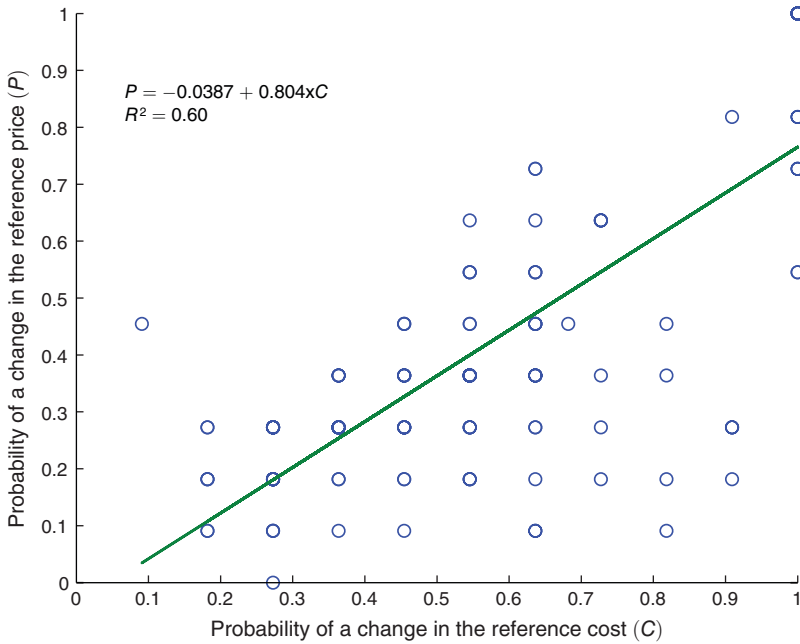


FIGURE 7

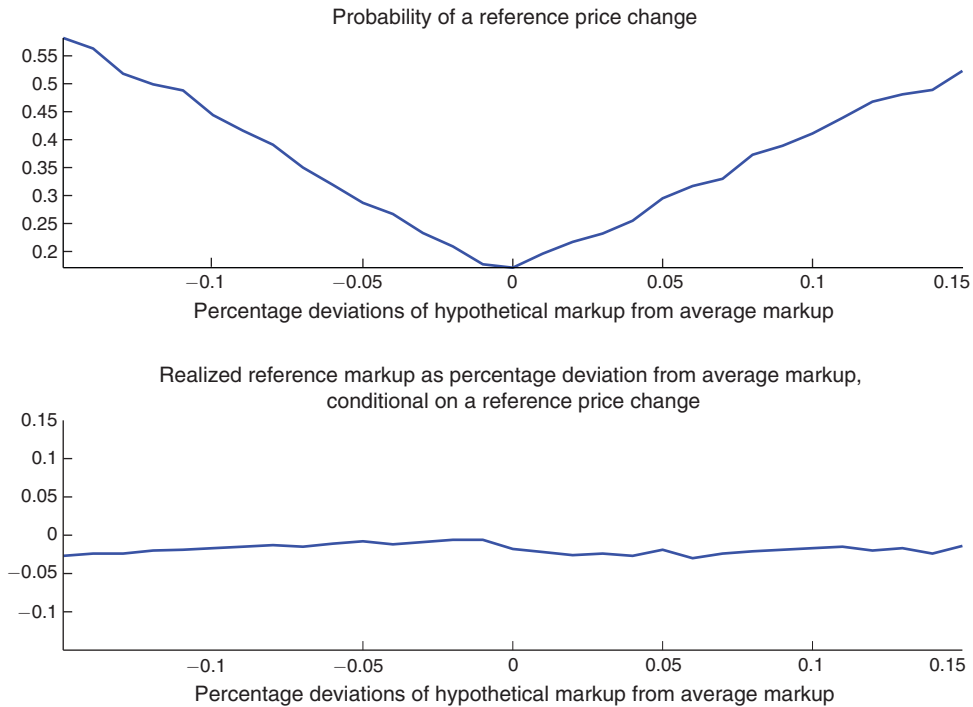


FIGURE 8

mean markup is very low. Strikingly, the larger is the percentage difference between the hypothetical reference markup and the average markup, the larger is the probability of a change in reference prices. So, there is clear evidence of a selection effect with regards to changes in reference prices. Figures 9 and 10 show that this selection effect continues to be present when we group individual items by reference price duration (Figure 9) and cost volatility (Figure 10). However, this selection effect is weaker in the categories that have short price durations.¹⁷ We interpret the similarity between Figures 9 and 10 as reflecting the negative correlation between price duration and cost volatility.

Suppose that a decision has been made to change the reference price. By how much does the reference price change? The bottom panel of Figure 8 displays the realized markup as a percentage deviation from the mean markup, conditional on the reference price changing. From this figure we see that the retailer sets the reference price so as to reestablish the average markup. Put differently, once the retailer decides to change its reference price, on average it passes through 100 percent of the cumulative change in reference cost that occurred since the last reference price change.

Figures 8 through 10 provide cross-sectional evidence on state dependence in the decision of changing reference prices. To provide time-series evidence on state dependence, we first compute the percentage deviations of the realized markup in periods with no price changes relative to the realized markup at the time of the price

¹⁷ We exclude the goods with duration zero and infinity from Figure 9. The price of goods with duration zero always changes. The price of goods with infinite duration never changes.

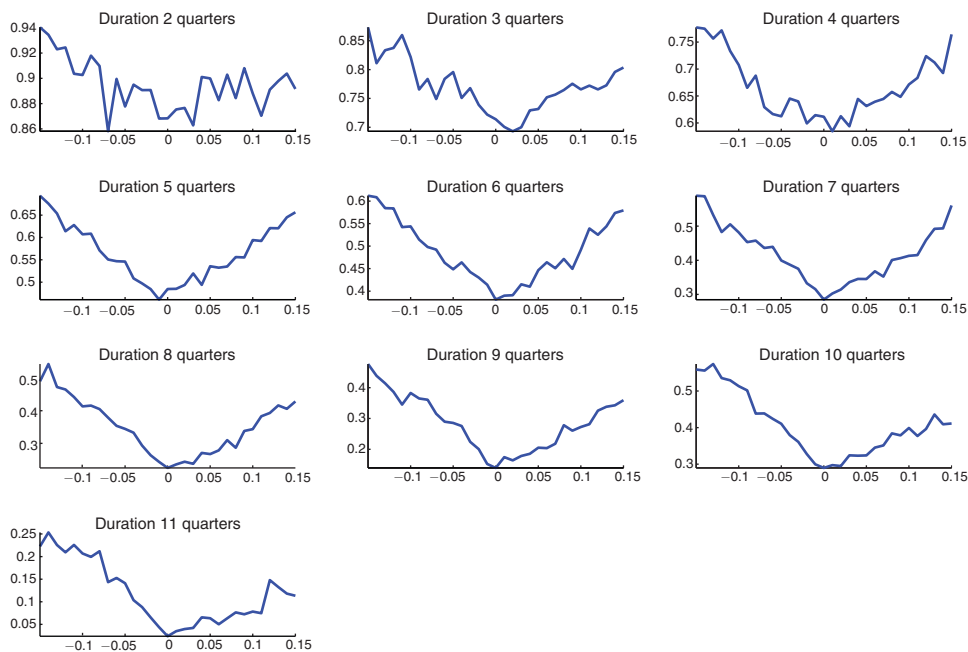


FIGURE 9. PROBABILITY OF REFERENCE PRICE CHANGE AS A FUNCTION OF PERCENTAGE DEVIATION OF HYPOTHETICAL MARKUP FROM AVERAGE MARKUP FOR GOODS WITH DIFFERENT PRICE DURATION

change. Figure 11 reports our results as a function of the number of periods prior to a price change. The key finding is that the markup falls (rises) monotonically over time as a function of the number of periods prior to a price increase (decrease).¹⁸

Taken together, these results support the hypothesis that the retailer chooses a reference price duration for each item to keep realized markups within bounds that are similar for different items.

V. Other Features of the Data

In this section we document two additional features of the data that are useful for evaluating the plausibility of different pricing models.

A. Volatility of Prices and Marginal Cost

In our dataset prices are more volatile than our measure of marginal cost. This result holds for weekly prices and costs as well as for reference prices and costs. The basic intuition for this result is that prices often do not change much in response to small changes in cost. But small cost changes that cumulate and create large deviations from the average markup can trigger very large changes in price. This pattern of behavior generates prices that have a larger standard deviation than cost.

¹⁸ We thank one of the referees for suggesting that we produce this figure.

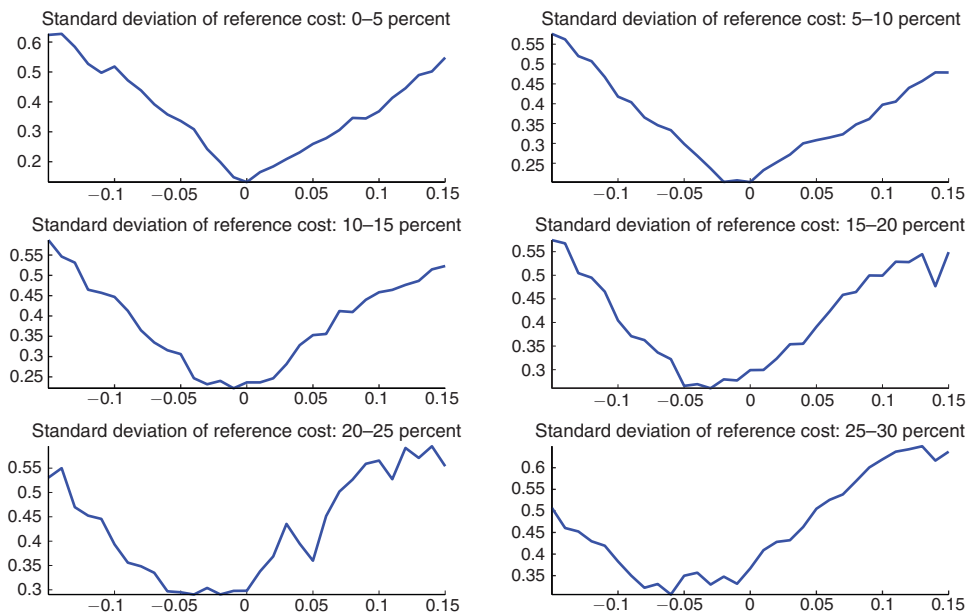


FIGURE 10. PROBABILITY OF REFERENCE PRICE CHANGE AS A FUNCTION OF PERCENTAGE DEVIATION OF HYPOTHETICAL MARKUP FROM AVERAGE MARKUP FOR GOODS WITH DIFFERENT COST VOLATILITY

The median of the ratio of the standard deviation of $\log(\text{weekly price})$ to the standard deviation of $\log(\text{weekly cost})$ is 1.08. The median of the ratio of the standard deviation of $\log(\text{reference price})$ to the standard deviation of $\log(\text{reference cost})$ is 1.15. We also find that prices are more volatile than costs if we focus on new prices and new costs or if we work in growth rates (see Table 2). We conclude that, regardless of whether we work with weekly or reference prices and costs, the volatility of prices generally exceeds that of marginal cost.

B. Demand Shocks

Conditional on the weekly price being constant and equal to the reference price, the standard deviation of quantities sold is roughly 42 percent.¹⁹ This conditional volatility is roughly 79 percent of the unconditional volatility of quantities sold. We infer that demand shocks are quantitatively important.

VI. Reconciling Different Pricing Models with Our Findings

In this section we discuss the implications of our empirical findings for three pricing models that are widely used in macroeconomics: flexible price models, menu cost models, and Calvo models.

¹⁹ A caveat to our calculation is that we are conditioning on the nominal price being constant instead of the real price being constant. By real price we mean the price of the good relative to the CPI basket. Since we focus on a short time period during which inflation is quite low, it seems unlikely that inflation effects are important for this calculation.

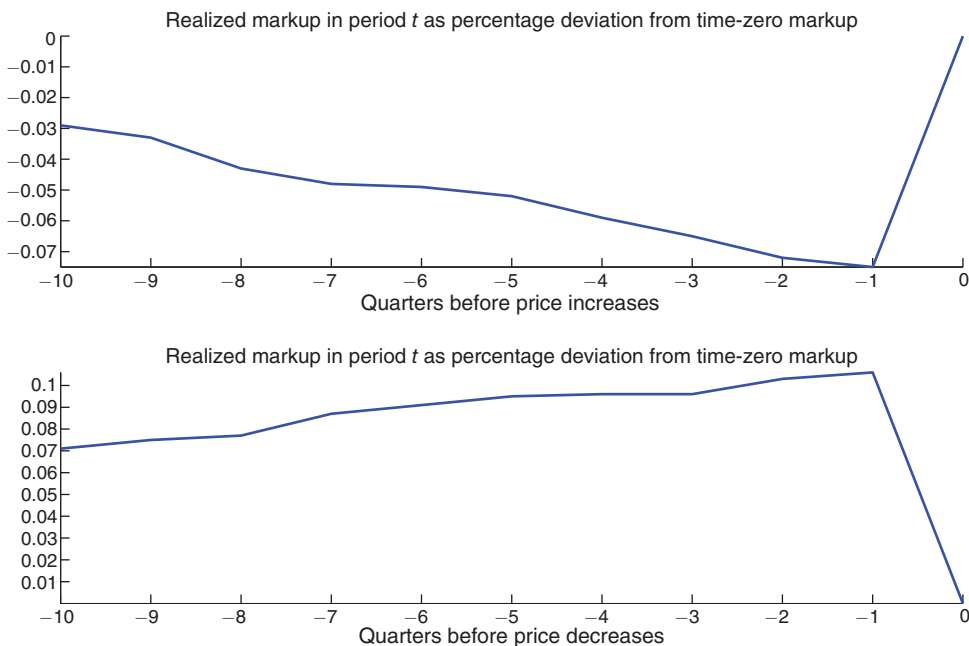


FIGURE 11

A. Flexible Price Models

The Dixit-Stiglitz model of monopolistic competition lies at the core of many flexible price macroeconomic models. In this model, the elasticity of substitution across different goods is constant. The optimal policy for each monopolist is to set the price (P_t) equal to a constant markup (μ) over marginal cost (C_t), $P_t = \mu C_t$. This model is clearly inconsistent with our data, since it implies that there should be no variation in the markup. Table 2 indicates that the standard deviation of the logarithm of the realized weekly markup and reference markup is 0.11 and 0.09, respectively.

It is possible to reconcile a flexible price model with the data by introducing demand shocks that generate markup fluctuations. But matching the data requires an incredible configuration of cost and demand shocks. Consider the following simple specification in which demand is linear:

$$P_t = a_t - b_t Q_t,$$

where Q_t represents the quantity sold. The variables a_t and b_t are stochastic demand shifters. Variable profits, π_t are given by: $\pi_t = P_t Q_t - C_t Q_t$, where C_t is the monopolist's cost. The monopolist's optimal price and quantity are given by

$$P_t^* = \frac{a_t + C_t}{2},$$

$$Q_t^* = \frac{a_t - C_t}{2b_t}.$$

TABLE 4—CORRELATION PROPERTIES

<i>Correlations, primary dataset</i>				
	ln(weekly price)	ln(weekly quantity)	ln(weekly cost)	ln(weekly markup)
ln(weekly price)	1	-0.47	0.71	0.51
ln(weekly quantity)		1	-0.28	-0.20
ln(weekly cost)			1	-0.34
ln(weekly markup)				1
<i>Correlations, Dominick's dataset</i>				
	ln(reference price)	ln(reference quantity)	ln(reference cost)	ln(reference markup)
ln(reference price)	1	-0.17	0.44	0.70
ln(reference quantity)		1	0	-0.19
ln(reference cost)			1	-0.49
ln(reference markup)				1
<i>Correlations, Dominick's dataset</i>				
	ln(weekly price)	ln(weekly quantity)		
ln(weekly price)	1	-0.37		
ln(weekly quantity)		1		
	ln(reference price)	ln(reference quantity)		
ln(reference price)	1	-0.05		
ln(reference quantity)		1		

Changes in b_t affect only the quantity sold. Changes in a_t affect both price and quantity. Given observations on P_t^* , Q_t^* , and C_t , we can deduce the time series for a_t and b_t such that P_t^* and Q_t^* match the data exactly. We perform this calculation for each of the items in our sample. Three key results emerge. First, the median standard deviation of $\log(a_t)$ and $\log(b_t)$ are 0.16 and 0.77, respectively. So, to match the data the variable a_t must be roughly as volatile as prices and cost (see Table 2). The volatility of b_t must be higher than the volatility of quantities and roughly four times more volatile than prices and costs. We conclude that an empirically plausible flexible price specification must allow for volatile demand shocks. Second, the correlation between $\log(a_t)$ and $\log(b_t)$ is positive (0.7). This positive correlation helps the model match the negative unconditional correlation between prices and quantities, reported in Table 4, while allowing for volatile demand. Third, and most importantly, matching the data requires an implausible pattern of comovement between a_t and C_t . In at least 40 percent of our observations the same price corresponds to different costs.²⁰ To match these observations, the change in a_t must *exactly* offset the change in C_t . Although possible, this pattern of shocks strikes us as incredible.

A similar argument applies to Dixit-Stiglitz demand with stochastic elasticity of substitution between goods. This specification generates variability in markups. However, it requires that in 40 percent of the observations shocks to the elasticity of substitution exactly offset movements in marginal cost in order to rationalize a constant price.

²⁰ This statistic is computed as follows. For each good we identify the modal price and cost over the three-year sample period. We then compute the fraction of weeks in which the price is equal to the modal price but the cost is not equal to the modal cost. This calculation provides a lower bound on the percentage of weeks in which the same price corresponds to different costs.

B. Menu Cost Models

Standard menu cost models have three shortcomings with respect to our data. First, Table 2 documents that prices are more volatile than marginal cost, whether we work with levels or growth rates. However, calibrated versions of menu cost models imply that prices are *less* volatile than marginal cost. For example, Golosov and Lucas' (2007) model implies that the unconditional standard deviation of cost changes is 40 percent more volatile than the unconditional standard deviation of price changes. A similar pattern obtains in Ariel T. Burstein and Christian Hellwig's (2007) model, which incorporates demand shocks into the Golosov-Lucas framework. The unconditional standard deviation of cost changes is twice as large as the unconditional standard deviation of price changes in the Burstein-Hellwig model.²¹ Second, we need an incredible configuration of cost and demand shocks to explain why firms return often to an old (reference) price. Third, as we discuss in Section VII, it is difficult for menu cost models to match both the frequency of weekly price changes and the frequency of reference price changes.

Kehoe and Midrigan (2007) make progress on the second shortcoming by assuming that firms set two kinds of prices, "regular" prices and "sale" prices. Sale prices are temporary price reductions. After a sale is over the price returns to the "regular" price. Kehoe and Midrigan assume that the menu cost associated with a sale price change is lower than the menu cost associated with a regular price change. It remains an open question whether such a model can rationalize the fact that prices, both weekly and reference, are more volatile than marginal cost.

C. Calvo Models

Perhaps the most widely used pricing model in macroeconomics is the one associated with Guillermo A. Calvo (1983).²² An obvious failing of the standard Calvo (1983) pricing model is that it is inconsistent with the selection effects that we document in Figures 8–10. The Calvo model assumes that the probability of a price change is constant. In fact, we find that the probability of a reference price change is increasing in the deviation of the hypothetical markup from its unconditional mean. It also remains an open question whether standard Calvo pricing models are useful to understand datasets like ours in which prices are more volatile than costs.

VII. Are Reference Prices Useful for Macroeconomists?

In this section we consider a simple partial-equilibrium model that accounts for the key features of the data that we document in Sections II and III. In this model monetary policy shocks have important real effects even though weekly prices change very frequently. We use this model to illustrate the sense in which the frequency of reference price changes can be a useful statistic to guide macroeconomists.

²¹ We thank Ariel Burstein for computing the volatility of prices and costs in the Golosov-Lucas model and in the Burstein-Hellwig model.

²² See, for example, Julio J. Rotemberg and Michael Woodford (1997); Jordi Galí and Mark Gertler (1999); Frank Smets and Raf Wouters (2003); and Lawrence Christiano, Eichenbaum, and Charles L. Evans (2005).

In our model the firm chooses a “price plan” which consists of a small set of prices, Ω .²³ The firm can move between prices in this set without incurring any cost, i.e., there are no menu costs of changing between prices in Ω . The key friction is that there is a fixed cost, ϕ , of changing the price plan.

The firm faces the following demand and cost functions:

$$Q_t = \mu_t P_t^{-\alpha_t},$$

$$C_t = \mu_t^{1/\alpha} c_t Q_t,$$

where Q_t and P_t denote the quantity and price, respectively. The variable C_t denotes the cost of production. The variables α_t and c_t represent shocks to the elasticity of demand and cost, respectively.

We want to mimic the effect of a monetary shock in our simple model. We take the defining characteristic of such a shock to be that, absent pricing frictions, it has no effect on quantities. The variable μ_t , which affects both demand and cost, has this property. If prices are completely flexible, a 1 percent rise in μ leads to a $1/\alpha$ percent rise in prices and has no effect on quantities sold. For this reason we refer to μ_t as a monetary policy shock.

Let s and $F(s'|s)$ denote the triplet $\{\alpha, c, \mu\}$ and the conditional density of s' given s , respectively. We denote by $V(\Omega, s)$ the value of the firm when there is no change in its price plan, Ω , and the state of the world is s . Let $W(s)$ be the value of the firm when it changes its price plan. These two value functions are given by

$$V(\Omega, s) = \max_{P \in \Omega} [\mu P^{1-\alpha} - \mu^{(1+\alpha)/\alpha} c P^{-\alpha}]$$

$$+ \beta \int \{\max [V(\Omega, s'), W(s')]\} dF(s'|s),$$

and

$$W(s) = \max_{P \in \Omega', \Omega'} \left\{ \mu P^{1-\alpha} - \mu^{(1+\alpha)/\alpha} c P^{-\alpha} - \phi \right.$$

$$\left. + \beta \int \{\max [V(\Omega', s'), W(s')]\} dF(s'|s) \right\}.$$

The standard menu-cost model is a special case of this model where the set Ω is a singleton.

A. Model Calibration

The free parameters of the model are ϕ , β , and those governing the laws of motion for the three shocks, α , c , and μ . In choosing parameter values we assume that a

²³ Burstein (2006) considers a different formulation of price plans in which firms choose a deterministic price sequence. Bernardo Guimaraes and Kevin Sheedy (forthcoming) consider a model in which there are Calvo-style frictions associated with the reference price but firms can costlessly vary their sale frequencies and sale discounts.

TABLE 5—DATA AND MODEL STATISTICS

	Data	Sticky plan model	Menu cost calibrated to the frequency of weekly price changes	Menu cost model calibrated to frequency of reference price changes
Menu cost value as percentage of steady state cash flow		0.0525	0.0100	0.4593
Weekly cost volatility	0.120	0.112	0.113	0.112
Weekly price volatility	0.140	0.111	0.113	0.075
Weekly quantity volatility	0.530	0.600	0.599	0.416
Frequency of weekly price changes	0.430	0.375	0.402	0.155
Frequency of weekly cost changes	0.490	0.577	0.574	0.576
Frequency of reference price changes	0.270	0.268	0.670	0.269
Frequency of reference costs changes	0.450	0.634	0.628	0.635
Fraction of price changes without cost changes	0.030	0.011	0.009	0.003
Frequency of plan change		0.023		

unit of time in the model is one week. Also, we assume that Ω consists of only two prices. This choice is motivated by computational considerations and the fact that in our data the typical good spends 75 percent of the time at the two most frequently observed prices within a quarter.²⁴ We then choose the parameters of the model to match, as closely as possible, the moments of the data listed in Table 5. We compute the frequency of reference price changes using the same algorithm that we use in our empirical work. Specifically, we simulate the model and calculate the reference price as the modal price per quarter.

We set β equal to 0.999. We assume that α and μ can take on two values, while c can take on three values: $\alpha \in \{5.25, 7.5\}$, $\mu \in \{1, 1.15\}$, and $c \in \{0.85, 1.08, 1.10\}$. The three shocks are independent of each other and are governed by first-order Markov chains. We denote the transition matrix of shock i by π^i . The three transition matrices are given by:

$$\pi^\alpha = \begin{bmatrix} 0.99 & 0.01 \\ 0.15 & 0.85 \end{bmatrix},$$

$$\pi^c = \begin{bmatrix} 0.3881 & 0.4838 & 0.1281 \\ 0.2714 & 0.5472 & 0.1814 \\ 0.2116 & 0.4968 & 0.2916 \end{bmatrix},$$

and

$$\pi^\mu = \begin{bmatrix} 0.95 & 0.05 \\ 0.05 & 0.95 \end{bmatrix}.$$

The serial correlation of the logarithm of α , μ , and c is 0.84, 0.90, and 0.14, respectively. So, cost shocks are less persistent than the other shocks. The standard deviation of the logarithm of α , μ , and c is 0.09, 0.07, and 0.11, respectively. So, monetary policy shocks are less volatile than the other shocks.

²⁴ The probability of moving from the two most frequent prices to some other price is only 1 percent.

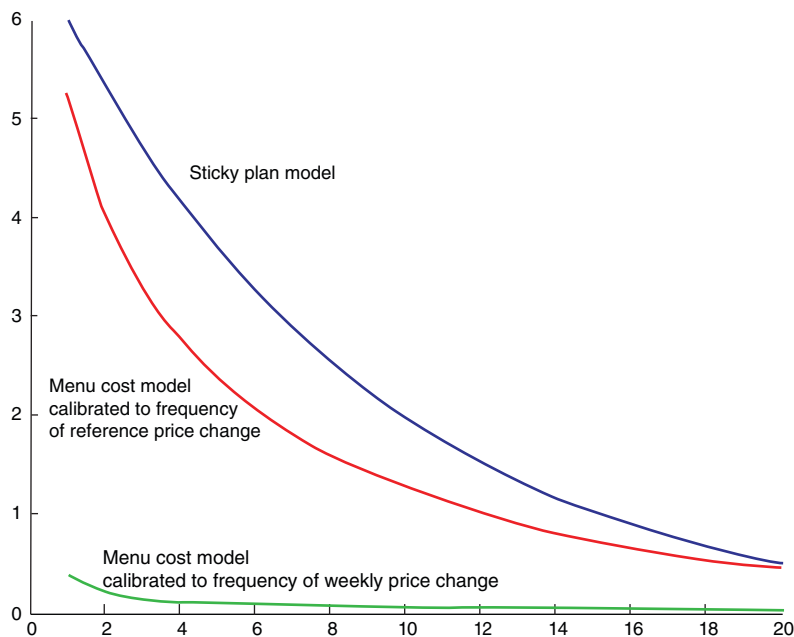


FIGURE 12. IMPULSE RESPONSE TO A MONETARY SHOCK

The size of the menu cost plays a key role in determining how often the firm changes its price plan. We chose a menu cost (5 percent of weekly revenue) which implies that the plan changes very infrequently (2 percent of the time). This choice allows us to illustrate the point that, even when plans change infrequently, prices can change very frequently.

From Table 5 we see that a change in the reference price is an imperfect indicator of a change in the price plan. But, as we argue below, even with this calibration, focusing on the frequency of reference price changes is useful for assessing the quantitative effects of a monetary policy shock. Table 5 also indicates that the model does a reasonable job at accounting for the volatility of costs, prices, and quantities, the frequency of price and cost changes, and the fraction of price changes that are not accompanied by cost changes. On this basis we conclude that we are working with a reasonable calibration.

We now turn to the effects of a monetary policy shock in the model. The top line in Figure 12 displays the response of quantities sold by the firm to a monetary policy shock of 15 percent.²⁵ Notice that the shock leads to a substantial, prolonged increase in quantities sold. So, even though weekly prices change very frequently in our model, a monetary policy shock has large effects. This result reflects the fact that a monetary policy shock does not induce a change in the price plan.

²⁵ This impulse response function is computed as the average response of quantities sold after a monetary shock, expressed as percentage deviations from the unconditional average of quantities sold. We compute this impulse response function in population by combining the transition matrix of the exogenous shocks with the policy functions associated with the model.

While our model is consistent with both the frequency of price changes and the frequency of reference price changes, it has a larger state space. As a consequence our model is harder to solve from a computational standpoint than standard menu cost models. A natural question is whether a menu cost model can provide a reasonable approximation to our model in terms of reproducing the effects of a monetary policy shock. But if we calibrate the standard menu cost model to be consistent with the frequency of weekly price changes, the answer is no.²⁶ If we calibrate the standard menu cost model to be consistent with the frequency of reference price changes, the answer is yes.

To substantiate these claims we proceed as follows. First we specialize our model so that Ω contains only one element. Under this assumption we obtain the standard menu-cost model. We then choose a value for the menu cost so that the model is consistent with the frequency of weekly price changes observed in our dataset. This exercise is the spirit of the analysis in Golosov and Lucas (2007). Because prices change so frequently we must choose a menu cost that is very small compared to the cost of changing the price plan (1 percent versus 5 percent of weekly sales). As can be seen from Table 5, the resulting menu cost model does as well as our sticky plan model with one important exception: it greatly overstates the frequency of reference price changes (0.67 versus 0.27). From Figure 12 we see that this menu cost model erroneously implies that a monetary policy shock has almost no effect on quantities sold. This property follows directly from the small size of the menu cost which induces the firm to change prices in response to almost all shocks. So, if we insist that the menu cost model reproduce the frequency of price changes, we are led to the misleading conclusion that a monetary policy shock has a very small effect on real economic activity.

Consider next the same menu cost model where the size of the menu cost is chosen so that the frequency of reference price changes is the same as in our sticky plan model. Because reference prices change less frequently than weekly prices, we are led to a much higher value of the menu costs than in the other version of our menu cost model (46 percent versus 1 percent of weekly sales). This version of the model does not do as well as the other menu cost model at matching the weekly volatility of prices and quantities. But from Figure 12 we see that this version of the menu cost model does much better than the other menu cost model at reproducing the effect of a monetary policy shock. This example captures the idea that a lot of high-frequency volatility in prices and quantities has little to do with monetary policy and is perhaps best ignored by macroeconomists.

VIII. Conclusion

We present evidence that is consistent with the view that nominal rigidities are important. However, these rigidities do not take the form of sticky prices, i.e., prices that remain constant over time. Instead, nominal rigidities take the form of inertia in reference prices and costs. Weekly prices and costs fluctuate around reference values which tend to remain constant over extended periods of time. Reference prices are particularly inertial and have an average duration of roughly one year. So, nominal

²⁶ This exercise is similar in spirit to the analysis in Kehoe and Midrigan (2007).

rigidities are present in our data, even though prices and cost change very frequently, roughly once every two weeks. We document the relation between prices and costs and argue that reference prices and costs are useful statistics for macroeconomic analysis.

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