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Retail Prices for Milk by Fat Content: A New Theory and Empirical Test of Retailer Pricing Behavior

Tian Xia and Richard J. Sexton

We study a heretofore unexamined type of product differentiation, horizontally differentiated products with differential costs, and apply the analysis to retail pricing of fluid milk products. The theoretical models yield unique predictions for the relationship among prices of the four horizontally differentiated fluid milk products (skim, 1%, 2%, and whole milk) and the impacts of butterfat and nonfat milk costs on prices, depending upon the form of retail competition. An empirical analysis of retail milk pricing for four major cities in California enables tests to be conducted of which form of behavior best characterizes grocery retailing in these cities.

Key words: differential costs, horizontal differentiation, milk, oligopoly, retail pricing

Introduction

Product differentiation is generally classified as one of two types. With horizontal differentiation, consumers differ in their ranking of product varieties, as in the Hotelling model. Differentiation is vertical when consumers agree on the ranking of products, but differ as to the intensity of their preference, as in a Mussa-Rosen model. Production costs play no central role in most models of horizontal differentiation; all products and all sellers have the same, constant unit cost (e.g., Tirole, 1988; Mas-Colell, Whinston, and Green, 1995). With vertical differentiation, it is natural that it is more costly to produce higher-ranked products (Mussa and Rosen, 1978; Shaked and Sutton, 1982).

In this paper we study a heretofore unexamined type of product differentiation and apply the analysis to retail pricing of fluid milk products. We describe this case as horizontally differentiated products (HDP) with differential costs. Fluid milk products are differentiated based on fat content. Consumers are horizontally differentiated in their preferences for fat content of milk. Some prefer skim or low-fat milk because they do not want to consume calories associated with butterfat, while others choose whole milk because it tastes better and/or they believe it is more nutritious. Butterfat, however, is the most expensive component in milk, so fluid milk features differential costs. Among the four types of fluid milk commonly sold, a clear cost ranking exists, with skim milk being cheapest, followed by 1%, 2%, and whole milk.[1]

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[1] Other examples of foods featuring horizontal differentiation with differential costs would include products with differing sugar contents. Because sugar is an expensive ingredient, within a product category foods with higher sugar content are more expensive to produce, but consumers are differentiated in their preferences based upon their willingness to trade off taste for caloric content. Applications to nonfood products also exist.

We develop the theory of pricing for HDP with differential costs in the context of retail fluid milk pricing for three market structures—perfect competition, monopoly, and oligopoly—for the four horizontally differentiated fluid milk products (skim, 1%, 2%, and whole milk) typically offered by U.S. food retailers, but the results generalize readily to more or fewer products. The theoretical models yield unique predictions for the relationship among prices of the four milk products and the impacts of butterfat and nonfat milk costs on prices, depending on the form of retail competition. Thus, the empirical analysis of retail milk pricing for four major cities in California enables tests to be conducted of which form of behavior—perfect competition, oligopoly, or monopoly—best characterizes grocery retailing in the four California cities studied.

The Model

We study retailers who procure fluid milk products from competitive processors/wholesalers. Retailers' selling costs for the horizontally differentiated milk products are assumed to be constant per unit and identical across types of milk. Without loss of generality, these costs are set to zero. Retailers sell four HDP of fluid milk (skim, 1%, 2%, and whole milk), and are assumed to set prices to maximize profits for the milk category. The butterfat contents that distinguish the milk products are assumed to be predetermined in this model; hence, we do not study any prior decision regarding which HDP to design and sell.

Raw milk is processed by first separating it by component and then the various components are reassembled according to different content formulas to make the final products, such as different types of fluid milk. Thus it is reasonable to assume that processing costs are the same for the four types of fluid milk, in which case they can be ignored and the unit variable procurement costs of the four products can be written as C_0, $C_1 = 0.99C_0 + C_f$, $C_2 = 0.98C_0 + 2C_f$, and $C_3 = 0.965C_0 + 3.5C_f$, where subscripts 0, 1, 2, and 3 represent skim, 1%, 2%, and whole milk, respectively. $C_0 > 0$ is the unit cost of nonfat content of milk (skim milk) in \$/100 lbs.[2] $C_f > 0$ is the unit cost of butterfat in \$/lb.[3] The cost difference between any two adjacent milk products is proportional to the difference between the butterfat and nonfat cost, $C_f - 0.01C_0$, and thus is increasing in C_f and decreasing in C_0.

The Hotelling framework is adopted to model the milk products' horizontally differentiated attribute, the fat content, and consumers' heterogeneous preferences. The fat content of a milk product is denoted as q_j, where $q_0 = 0$, $q_1 = 1$, $q_2 = 2$, and $q_3 = 3.5$. We assume that consumers' preferences for the fat content, θ, are uniformly distributed over the range [0, 3.5].[4] A consumer is assumed to either purchase one unit of a milk product or make no purchase. The total number of consumers is constant when the market is covered and is set to $N = 1$ by normalization.

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[2] The nonfat content of milk itself contains components such as proteins, carbohydrates, and minerals. Our approach in the conceptual model is to treat the ingredient content of skim milk as an aggregate component. This approach is consistent with the way California farmers are paid for raw milk, and these component prices form the basis for the subsequent empirical tests.

[3] Different measurement units for the nonfat and fat cost are used to simplify the mathematical expressions in the conceptual and econometric models.

[4] The assumption of a uniform distribution of consumers is standard in applications of the Hotelling model, and it markedly simplifies exposition. Although specific analytical solutions for prices and market shares depend on the distributional assumption, the results about the direction and relative magnitude of effects of various cost and demand factors on four milk prices and market shares, which represent the core of the analysis, are robust to any other type of continuous distribution of consumer preferences.

Following the standard Hotelling model formulation (e.g., Salop, 1979; Tirole, 1988; Mas-Colell, Whinston, and Green, 1995), a consumer derives a gross benefit (utility) of u from consuming his preferred product. The total cost of buying one unit of product j = 0, 1, 2, 3 consists of a monetary cost P_j (the retail price of product j), and a disutility cost $r(\theta - q_j)^2 \geq 0$ of consuming an alternative to his preferred product, where $r > 0$ is the consumer's disutility rate and represents a measure of the strength of substitution among the HDP. A strictly convex function for the consumer's rate of disutility from consuming an alternative to his preferred product type implies, as seems realistic, that disutility is increasing at an increasing rate in the difference in fat content between the alternative and ideal products. A consumer's net utility of buying a unit of product j is thus $U(\theta, q_j, P_j) = u - r(\theta - q_j)^2 - P_j$. The reservation utility when a consumer does not purchase this product is $u = 0$. To make certain the market exists—i.e., for each product there are some consumers who are willing to buy it at the lowest possible price—its unit variable costs, the condition $u > C_j$ is assumed to hold for all j.

If the cost differences among the HDP are too large relative to the consumer disutility rate r, a retailer may not sell the products with higher costs (e.g., whole milk). To avoid this uninteresting equilibrium, the market share of all milk products in the model always must be positive. Based on the results in the next section, the market share of whole milk under perfect competition, $S_3^K = 3/14 - (C_f - 0.01C_0)/7r$, is the smallest among the market shares under all competition scenarios. By setting $S_3^K > 0$, we find and impose the condition $1.5r > C_f - 0.01C_0$, which ensures all four types of milk products are offered and purchased in equilibrium.

Perfect Competition

We now examine the market equilibrium for horizontally differentiated milk products with differential costs under three competition scenarios: perfect competition, monopoly, and oligopoly. If the retail market for milk products is perfectly competitive, any attempt by a retailer to raise prices above unit variable procurement and selling costs will cause all of her customers to switch to other retailers. Thus, a competitive retailer's equilibrium prices (superscript K) for the four types of milk products are equal to their respective unit costs. Specifically, $P_j^K = C_j$, with j = 0, 1, 2, 3. Thus, the butterfat cost C_f does not affect the retail price of skim milk. Cost changes of fat and nonfat contents of milk are reflected fully in changes in the sales price. Demand, as reflected in consumers' utility parameters u and r, has no effect on the retail prices of the four products.

Demands for individual products in a Hotelling model are derived by first finding the consumers who are indifferent between purchasing two products that are located adjacent to each other in the product space. For example, consumers with preference $\theta_{0,1}^K$ are indifferent between consuming skim and 1% milk, where $\theta_{0,1}^K = 1/2 + (C_1 - C_0)/2r$ is found from solving the condition $U(\theta_{0,1}^K, q_0, P_0) = U(\theta_{0,1}^K, q_1, P_1)$. All consumers with $\theta < \theta_{0,1}^K$ strictly prefer to consume skim milk relative to the alternatives, given the prices. Similarly, we find that consumers with preference $\theta_{1,2}^K = 3/2 + (C_2 - C_1)/2r$ are indifferent between consuming 1% and 2% milk, and consumers with preference $\theta_{2,3}^K = 2.75 + (C_3 - C_2)/3r$ are indifferent between consuming 2% and whole milk. Indifferent consumers are assumed to buy the product with the lower cost, so consumers with preferences in the ranges $[0, \theta_{0,1}^K]$, $(\theta_{0,1}^K, \theta_{1,2}^K]$, $(\theta_{1,2}^K, \theta_{2,3}^K]$, and $(\theta_{2,3}^K, 3.5]$ buy skim, 1%, 2%, and whole milk, respectively (see figure 1).

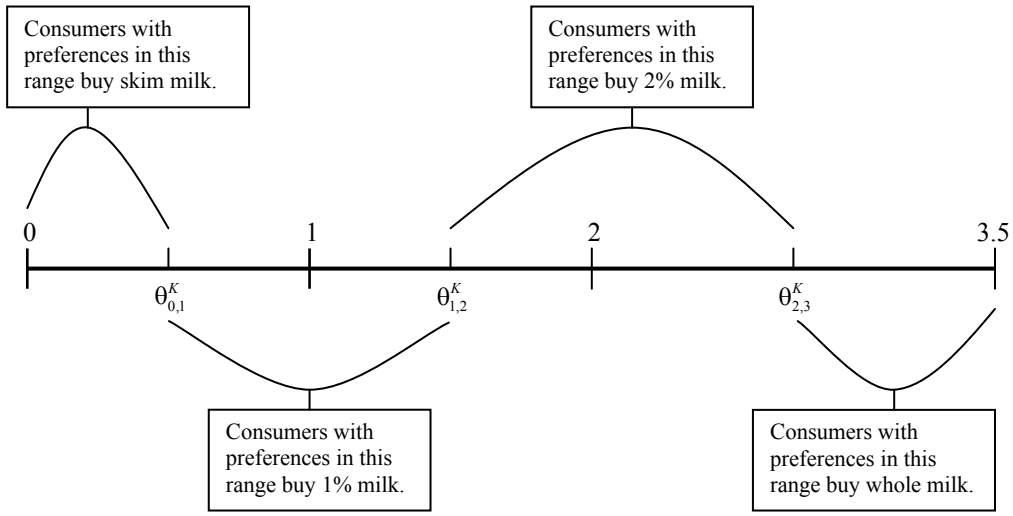

Figure 1. Illustration of the four consumer preference ranges

Given the locations of the indifferent consumers, the market shares for each of the four milk products under the uniform distribution of consumers are written as:

$$S_0^K = \theta_{0,1}^K / 3.5 = 1/7 + \left(C_f - 0.01C_0\right)/7r,$$
$$S_1^K = (\theta_{1,2}^K - \theta_{0,1}^K) / 3.5 = 2/7,$$
$$S_2^K = (\theta_{2,3}^K - \theta_{1,2}^K) / 3.5 = 5/14,$$

and

$$S_3^K = (3.5 - \theta_{2,3}^K) / 3.5 = 3/14 - \left(C_f - 0.01C_0\right)/7r.$$ [5]

An increase in butterfat cost and/or a decrease in nonfat cost will cause an increase in the cost differences among milk products. The increase in the cost differences is reflected fully in the price differences, causing more consumers to purchase skim milk whose cost is lowest and fewer consumers to purchase whole milk whose cost is highest. A higher disutility rate makes consumers more reluctant to consume an alternative to their preferred product, ceteris paribus. Hence, fewer consumers will buy skim milk which is cheapest and more consumers will buy whole milk which is the most expensive, the higher is the disutility rate r. The cost differences and the disutility rate do not affect the market shares of 1% and 2% milk, given a uniform distribution of consumers. In each case an increase in the cost difference or a decrease in the disutility rate causes some consumers to switch to a lower-cost product, but also attracts the same number of consumers who previously purchased a higher-cost product.

[5] To see these derivations more clearly, substitute the equations for the $\theta_{i,j}^K$ and recall that the cost differences for two adjacent milk products can be written as $C_j - C_{j-1} = C_f - 0.01C_0$ for $j = 1, 2$, and $C_3 - C_2 = 1.5C_f - 0.015C_0$.

Monopoly

Now consider a model where each retailer is able to set price as a monopolist does, due, e.g., to high spatial differentiation among multiple retailers in a city. The monopoly model involves two cases, depending on whether the market is covered (all consumers purchase a milk product) or not. When the market is not covered, some consumers with middle-range preferences do not buy any of the four products in equilibrium. In this case, the pricing decisions of at least two products are not interdependent so that a retailer sets the monopoly prices for these products independently.

Whether it is optimal for a monopoly seller to cover the market depends on the model parameters.[6] The tradeoff is that reducing price sufficiently to serve customers with middle-range preferences increases sales, but reduces the profit margin of sales relative to what could be attained by limiting sales to those consumers whose preferences for butterfat content are in the vicinity of the fat contents of the four available fluid milk products. We focus here on the case where the market is covered, which seems the relevant emphasis—i.e., there is no evidence that consumers do not purchase fluid milk because they cannot obtain their desired fat content. Analysis of the not-covered case, including derivation of the restrictions on the model parameters necessary for the market to be covered, is provided in the working-paper version of this study (Xia and Sexton, 2009).

In the covered-market case, there are three types of consumers who are indifferent between buying two adjacent types of milk. Consumers with preferences

$$\bar{\theta}_{0,1} = 1/2 + \left(P_1 - P_0\right)/2r, \quad \bar{\theta}_{1,2} = 3/2 + \left(P_2 - P_1\right)/2r, \text{ and } \quad \bar{\theta}_{2,3} = 2.75 + \left(P_3 - P_2\right)/3r$$

are indifferent between buying skim and 1% milk, 1% and 2% milk, and 2% and whole milk, respectively. Thus, consumers with preferences in the ranges $[0, \bar{\theta}_{0,1}]$, $(\bar{\theta}_{0,1}, \bar{\theta}_{1,2}]$, $(\bar{\theta}_{1,2}, \bar{\theta}_{2,3}]$, and $(\bar{\theta}_{2,3}, 3.5]$ buy skim, 1%, 2%, and whole milk, respectively. The retailer's profit from the milk category is represented by:

$$\pi(P_j) = \sum_{j=0}^{3} \left(P_j - C_j\right) S_j, \tag{1}$$

where $S_0 = \bar{\theta}_{0,1}/3.5$, $S_1 = \left(\bar{\theta}_{1,2} - \bar{\theta}_{0,1}\right)/3.5$, $S_2 = \left(\bar{\theta}_{2,3} - \bar{\theta}_{1,2}\right)/3.5$, and $S_3 = \left(3.5 - \bar{\theta}_{2,3}\right)/3.5$ are the market shares of the four products.

PROPOSITION 1. *At the profit-maximizing prices, consumers who are indifferent between buying two adjacent milk products receive their reservation utility, i.e., they are also indifferent between buying either type of product and not buying at all.*

To prove this argument, suppose the opposite is true, namely that (P_0', P_1', P_2', P_3') represents the set of profit-maximizing prices, and $U(\bar{\theta}_{j,j+1}, q_j, P_j') = U(\bar{\theta}_{j,j+1}, q_{j+1}, P_{j+1}') > \underline{u} = 0$ for j = 0, 1, 2. Then raising all four prices by a small amount, ε > 0, does not affect the values of the $\bar{\theta}_{j,j+1}$, so no consumer will change his purchase decision, but all consumers pay higher prices, increasing the retailer's profit and contradicting that (P_0', P_1', P_2', P_3') is profit maximizing. Thus, $U(\bar{\theta}_{j,j+1}, q_j, P_j) = U(\bar{\theta}_{j,j+1}, q_{j+1}, P_{j+1}) = 0$. Based on this result, we obtain:

[6] Specifically, it will be optimal for the seller to cover the market when u is large relative to the disutility (r) and cost factors (C_0 and C_f). See Xia and Sexton (2009) for the formal derivations.

(2) $$P_0 = P_2 = P_1 + 2\sqrt{(u - P_1)r} - r$$

and

(3) $$P_3 = P_1 - \sqrt{(u - P_1)r} - r/4.$$

Substituting (2) and (3) into (1), the monopoly retailer's optimization problem is written as:

(4) $$\begin{aligned}\max_{\{P_1\}} \pi = &\left(P_1 + 2\sqrt{(u-P_1)r} - r - C_0\right)\left(1 - \sqrt{(u-P_1)/r}\right) \\ &+ 2\left(P_1 + 2\sqrt{(u-P_1)r} - r - C_2\right)\sqrt{(u-P_1)/r} + (P_1 - C_1)\left(2 - 2\sqrt{(u-P_1)/r}\right) \\ &+ \left(P_1 - \sqrt{(u-P_1)r} - r/4 - C_3\right)\left(1/2 + \sqrt{(u-P_1)/r}\right).\end{aligned}$$

Solving the first-order condition to (4) and substituting the solution for P_1 back into (2), (3), and the market share equations, we find the equilibrium monopoly prices and market shares of the four milk products (superscript M):

$$\begin{aligned}
P_0^M &= P_2^M = u - \left(17r + 2C_f - 0.02C_0\right)^2 \big/ 784r, \\
P_1^M &= u - \left(11r - 2C_f + 0.02C_0\right)^2 \big/ 784r, \\
P_3^M &= u - \left(25r - 2C_f + 0.02C_0\right)^2 \big/ 784r, \\
S_0^M &= 17/98 + \left(C_f - 0.01C_0\right)\big/49r, \\
S_1^M &= 11/49 - 2\left(C_f - 0.01C_0\right)\big/49r, \\
S_2^M &= 17/49 + 2\left(C_f - 0.01C_0\right)\big/49r, \text{ and} \\
S_3^M &= 25/98 - \left(C_f - 0.01C_0\right)\big/49r.
\end{aligned}$$

Particularly interesting results are that (*a*) the price of skim milk, which does not contain butterfat, is decreasing in the butterfat cost C_f; (*b*) the 2% milk price is decreasing rather than increasing in the butterfat cost; while (*c*) the 1% and whole milk prices are increasing in the butterfat cost. The intuition for these surprising results is that the relative costs or the cost differences among milk products, rather than the absolute cost levels, determine the monopoly retailer's price decisions for situations when it is optimal for the retailer to cover the market. When the butterfat cost increases, the cost of whole milk increases relative to the cost of skim, 1%, and 2% milk. Higher relative cost gives the seller an incentive to increase the whole milk price. However, if it is optimal for the seller to keep the market covered, she must reduce the price of 2% milk to induce buyers near the whole–2% boundary, who would have purchased whole milk if not for its price increase, to continue to consume milk through buying 2% milk. Similarly, the covered-market monopolist increases the price of 1% milk and lowers the skim milk price in response to an increase in butterfat costs.[7]

[7] This result can be proven by showing that $\partial P_j / \partial P_{j+1} < 0$, based on equations (2) and (3). The skim and 2% milk prices are not necessarily equal to each other under other continuous distributions of consumer preferences in the covered-monopoly case. However, for any continuous distribution of consumer preferences, the skim and 2% milk prices change in the same direction (opposite to the direction of change in the 1% and whole milk prices) in response to a change in the butterfat cost.

Compared to the butterfat cost, the nonfat cost has an opposite effect on the cost difference between products. Thus, the effects of C_0 on milk prices are just the opposite to those of C_f. An increase in C_0 will lead to lower 1% and whole milk prices and higher skim and 2% milk prices under retailer monopoly. However, the effects of C_0 are in general much weaker than the effects of C_f due to the differential-cost aspect of the pricing problem.

All milk prices decrease when consumers incur a greater rate of disutility (a larger r) from consuming an alternative to their preferred product in the covered-market case. The retailer must lower all prices to entice consumers with preferences near the product-market boundaries to make purchases when a higher disutility rate makes it less attractive for those consumers to buy either type of product. All four prices are increasing in consumers' utility of consuming their preferred product because a higher utility for consumers enables the monopoly retailer to extract more consumer surplus by charging higher prices.

The market shares of two adjacent milk products will change in opposite directions in response to a change in the cost difference or the consumer disutility rate due to the monopoly retailer's optimal selling strategy to cover the market and let indifferent consumers receive only their reservation utility. An increase in C_f (decrease in C_0) results in a higher whole milk price and, accordingly, a smaller market share for whole milk. Even though 2% milk contains the second-highest butterfat content among the four milk products, the market share for 2% milk is increasing in C_f, while the market share of 1% milk is decreasing in C_f because its price rises. The market share of skim milk is larger when a higher C_f or a lower C_0 reduces the skim milk price. An increase in r causes a lower whole milk price so that the market share for whole milk will be larger. Similarly, the effects of r on the market shares of the other three milk products are also the opposite of the effects of the butterfat cost.

Oligopoly

We consider a simple duopoly market where two retailers, A and B, offer all four milk products to $N = 1$ consumers who do regular shopping in either one of these two stores.[8] The retailers are themselves horizontally differentiated in terms of store location and other characteristics. The procurement and selling costs and consumers' preference distribution are the same as those in previous scenarios. The consumers' preferences for location and other store characteristics are symmetrically distributed between the two stores. A consumer will buy one unit of a milk product from either store A or B or not buy milk at all to maximize his utility, making eight purchase choices and one no-purchase choice. A consumer's utility from purchasing one unit of product j from store n, where $n = A, B$, is

$$V\left[U(\theta, q_j, P_j), \mathbf{z}^n\right] = V\left[u - r(\theta - q_j)^2 - P_j, \mathbf{z}^n\right],$$

where $\mathbf{z}^n$ is a vector of the location and other store characteristics of store n.

We follow the general Bertrand model with product differentiation (Mas-Colell, Whinston, and Green, 1995, p. 395), and specify demand for each product as a function of its own price and the prices of all competing products. Given that $N = 1$, the demand for a milk product at a store is represented by its market share. Thus, we depict the market share of a

[8] Focus on duopoly is, of course, a simplification for modeling purposes, but it is not unrealistic for food retailing, where a key basis for differentiation among retailers is location in geographic space. As is well recognized in the spatial oligopoly literature (e.g., Salop, 1979), firms compete directly only with adjacent competitors.

milk product in a store as a linear function of its own retail price and the retail prices of all competing milk products in the two stores:[9] $\mathbf{S} = \boldsymbol{\lambda} + \boldsymbol{\Omega}\mathbf{P}$, where

$$\mathbf{S} = \left(S_0^A, ..., S_3^A, S_0^B, ..., S_3^B\right), \quad \boldsymbol{\lambda} = \left(\lambda_0^A, ..., \lambda_3^A, \lambda_0^B, ..., \lambda_3^B\right), \text{ and } \quad \mathbf{P} = \left(P_0^A, ..., P_3^A, P_0^B, ..., P_3^B\right)$$

are 8×1 vectors of market shares, intercepts, and prices, respectively, and $\boldsymbol{\Omega}$ is an 8×8 matrix of coefficients of prices. Using the conditions that (*a*) the sum of eight market shares is equal to 1, (*b*) consumers' preferences for location and other store characteristics are symmetrically distributed between the two stores, and (*c*) consumers' preferences are uniformly distributed, we have the following simplifications:

$$\lambda_j^n = 1/8 \text{ and } \boldsymbol{\Omega} = \begin{pmatrix} \mathbf{g} & \mathbf{h} \\ \mathbf{h} & \mathbf{g} \end{pmatrix}, \text{ with}$$

$$\mathbf{g} = \begin{pmatrix} -g_{00} & g_{01} & 0 & 0 \\ g_{01} & -g_{11} & g_{01} & 0 \\ 0 & g_{01} & -g_{11} & g_{01} \\ 0 & 0 & g_{01} & -g_{00} \end{pmatrix} \text{ and } \mathbf{h} = \begin{pmatrix} h_{00} & h_{01} & 0 & 0 \\ h_{01} & h_{11} & h_{01} & 0 \\ 0 & h_{01} & h_{11} & h_{01} \\ 0 & 0 & h_{01} & h_{00} \end{pmatrix},$$

where

$$g_{jj} > g_{01} > 0, \quad h_{jj} > h_{01} > 0, \quad -g_{00} + g_{01} + h_{00} + h_{01} = 0, \text{ and } \quad -g_{11} + 2g_{01} + h_{11} + 2h_{01} = 0.$$

The values of all g_{ij} and h_{ij} for $i, j = 0, 1$, and $i \leq j$ depend on the consumer disutility rate r and the store characteristics $\mathbf{z}^A$ and $\mathbf{z}^B$. To illustrate, the market share functions for skim and 1% milk of retailer *A* are:

$$S_0^A = 1/8 - g_{00}P_0^A + g_{01}P_1^A + h_{00}P_0^B + h_{01}P_1^B$$

and

$$S_1^A = 1/8 + g_{01}P_0^A - g_{11}P_1^A + g_{01}P_2^A + h_{01}P_0^B + h_{11}P_1^B + h_{01}P_2^B.$$

The structures of market share functions specify that a milk product competes directly with its adjacent substitutes. For example, 1% milk competes directly with skim and 2% milk sold within the same store and the competing store, and with 1% milk sold in the competing store, but not with whole milk. Some elements in **g** and **h** are zero for this reason. For instance, the third and fourth elements of the first row of **g** are zero because 2% and whole milk do not compete directly with skim milk in the same store. Similarly, the third and fourth elements of the first row of **h** are also zero because 2% and whole milk in the rival's store do not compete directly with skim milk in a retail store.

The profit functions of the two retailers are given by:

$$\pi^A = \sum_{j=0}^{3} \left(P_j^A - C_j\right) S_j^A = \pi^A \left(P_0^A, ..., P_3^A, P_0^B, ..., P_3^B \mid C_0, C_f\right)$$

and

$$\pi^B = \sum_{j=0}^{3} \left(P_j^B - C_j\right) S_j^B = \pi^B \left(P_0^B, ..., P_3^B, P_0^A, ..., P_3^A \mid C_0, C_f\right).$$

[9] This approach is similar to Nevo (2001), who specified the market share of a brand of ready-to-eat breakfast cereal as a function of its own retail price and the retail prices of all competing brands.

Retailer n ($n = A, B$) chooses prices P_0^n, P_1^n, P_2^n, and P_3^n to maximize profit π^n, given the prices charged by her rival. By deriving and solving eight first-order conditions simultaneously, we find the Nash equilibrium oligopoly prices (superscript O) of the four milk products:

$$P_j^O = P_j^{O,A} = P_j^{O,B} = \delta_j + \alpha_j C_f + \beta_j C_0,$$

with $j = 0, 1, 2, 3$, where δ_j, α_j, and β_j are functions of the cost and preference factors. Their detailed specifications are listed in the appendix due to their length. We find that $\delta_0 = \delta_3 > 0$, $\delta_1 = \delta_2 > 0$, $0 < \alpha_0 < \alpha_1 < \alpha_2 < \alpha_3 < 3.5$, $0.965 < \beta_3 < \beta_2 < \beta_1 < \beta_0 < 1$, and $\beta_j = 1 - 0.01\alpha_j$, for $j = 0, 1, 2, 3$. Notice that butterfat costs are not transmitted fully to the retail price of whole milk, but nonfat costs are transmitted in excess of 100%, whereas for skim milk an opposite result applies—a portion of a change in butterfat cost is transmitted to the retail price, even though it contains no butterfat, and transmission of nonfat costs is less than 100%. The positive transmission of butterfat cost for skim milk is opposite of the result for the covered-monopoly case.

In an oligopoly setting, a multi-product retailer has an incentive to coordinate the four prices based on relative costs in response to a butterfat or nonfat cost change, as in the covered-monopoly scenario, which means she has incentive to reduce skim and 2% milk prices when C_f increases. However, a butterfat cost increase results in higher whole and 1% milk prices in her rival's store, which have indirect positive effects on the 2% milk price of a retailer because the rival's prices are a strategic complement, as in the standard Hotelling model (i.e., an increase in retailer A's prices induces retailer B to charge higher prices, ceteris paribus). The sum of these two indirect positive effects is stronger than the negative effect of the butterfat cost increase on the retailer's 2% milk price due to her incentive to coordinate the four milk prices based on relative costs. Thus, overall, an increase in the butterfat cost results in a higher price for 2% milk. The similar logic applies to the skim milk price, which is also higher when C_f increases. For 1% and whole milk prices, when C_f increases, both the effect due to a retailer's coordination based on relative costs and the indirect effects of the increases in the rival's prices are positive. Therefore, 1% and whole milk prices in both stores increase when C_f increases.

The nonfat cost has two effects on milk prices. An increase in C_0 causes an increase in cost of all four milk products, which leads to higher prices for all products, and a decrease in the cost difference among products, which has the same price effects as in the monopoly scenario. The magnitude of the first effect is larger mainly because the increase in the absolute costs is much larger than the decrease in the relative cost. So, the nonfat cost is almost fully transmitted to the retail prices of the corresponding milk product. Unlike in monopoly, competition precludes duopolists from reducing the indifferent consumers' utility to their reservation utility. Thus, demand-side factors, represented in the model by consumers' utility (u) of consuming their preferred product, do not affect the product prices.

Although for the sake of tractability, these results were derived for duopoly, they apply to a general oligopoly setting. Specifically, any oligopoly seller has some market power over her own products, and thus has an incentive similar to the monopolist's to coordinate pricing across milk-product offerings as C_0, C_f, r, and u change. Competition from multiple rivals induces the same qualitative effects as in the duopoly case, but the relative strength of these effects increases when more rivals are present. Thus, although the specific analytical solutions depend on how many retailers are in the market, the results about the direction and relative

magnitudes of cost factors on four milk prices are robust to oligopoly with more than two retailers.

The effects of the cost and preference factors on product prices in the model under the alternative competition scenarios are summarized in table 1. The cost difference and the consumer disutility rate have quite different and interesting effects on product prices and market shares under the alternative competition scenarios. For example, although skim milk does not contain butterfat, an increase in C_f increases the cost difference among milk products, which will reduce the skim milk price of a monopoly retailer when the market is covered. Conversely, an increase in C_f increases the skim milk price in a duopoly setting, and has no effect on this price under perfect competition.

Our results are also quite different from those of standard monopoly and oligopoly models of a single product. The butterfat cost would have no effect on the skim milk price in single-product market-power models. A standard monopoly model predicts that an increase in the butterfat cost results in a higher price for 2% milk, opposite the prediction of the monopoly model in this analysis. Standard oligopoly models also predict that both the nonfat and butterfat costs are partially transmitted to the retail prices of the corresponding milk products. However, our oligopoly model shows the nonfat cost is almost fully transmitted to retail milk price. These differences are due to the fact that the model in this study captures how sellers with market power take into consideration two factors—the cost difference among milk products and consumer disutility rates of consuming an alternative product—when they choose the optimal retail prices for four milk products.

Empirical Application: Retail Milk Prices in California Cities

The conceptual models provide many testable predictions about the effects of various cost and preference factors on the prices and market shares of fluid milk products under the alternative competition scenarios. We focus mainly on the effects of the butterfat cost and the nonfat cost on retail milk prices, for which good data are available, and conduct hypothesis tests based on the conceptual results to characterize the competition for retail milk markets in four California cities. Pricing behavior and competition among grocery retailers is an important topic because retailers are widely regarded as the dominant players in the food chain in the United States (Calvin et al., 2001; Sexton, Zhang, and Chalfant, 2003), due in part to rising concentration and consolidation of sales among large supermarket chains. Ellickson (2007) calls grocery retailing a natural oligopoly because of the industry's ability to innovate continuously, most recently through the adoption of technology-intensive distribution systems in the 1980s and 1990s. [10]

Summaries of prior empirical work on food retailers' pricing behavior are provided by Cotterill (1993), Connor (1999), Wright (2001), Digal and Ahmadi-Esfahani (2002), and Sexton, Zhang, and Chalfant (2003). Much of this work has been conducted in the structure-conduct-performance framework. Most studies have found positive correlation between pricing and concentration in the food retail industry, but the entire approach has been the subject of considerable controversy and debate (chronicled in the aforementioned surveys), in part due to lack of conceptual foundations for the empirical models.

[10] Another important structural change in food retailing has been the rapid rise of Wal-Mart supercenters to become the leading food retailer in the United States. Various evidence, including for fluid milk (Cleary and Lopez, 2007), indicates Wal-Mart enhances competition in markets where it operates. Notably, supercenters were not present in California during the period of our empirical study.

Table 1. The Effects of Cost and Preference Factors on the Retail Prices of Four Types of Milk

Milk Product	Variable	Perfect Competition	Covered Monopoly	Oligopoly
Skim Milk	Butterfat Cost (C_f)	0	−	(0, 3.5)
	Nonfat Cost (C_0)	1	+	(0.965, 1)
	Disutility Rate (r)	0	−	NA
	Utility of Preferred Products (u)	0	+	0
1% Milk	Butterfat Cost (C_f)	1	+	(0, 3.5)
	Nonfat Cost (C_0)	0.99	−	(0.965, 1)
	Disutility Rate (r)	0	−	NA
	Utility of Preferred Products (u)	0	+	0
2% Milk	Butterfat Cost (C_f)	2	−	(0, 3.5)
	Nonfat Cost (C_0)	0.98	+	(0.965, 1)
	Disutility Rate (r)	0	−	NA
	Utility of Preferred Products (u)	0	+	0
Whole Milk	Butterfat Cost (C_f)	3.5	+	(0, 3.5)
	Nonfat Cost (C_0)	0.965	−	(0.965, 1)
	Disutility Rate (r)	0	−	NA
	Utility of Preferred Products (u)	0	+	0

Notes: The symbols +, −, and 0 denote positive, negative, and no effect, respectively. The positive numbers indicate the magnitudes of the effects of a one-unit increase of the corresponding variable. NA indicates the analytical result is not available due to the generalized specification of the market share function.

A second group of studies that are more closely related to the present study examine the transmission of price changes from farm to retail. These studies have investigated a hypothesis that retail prices respond only partially and with delay to changes in farm prices, and that response may be asymmetric, with retail prices responding faster and more completely to price increases than price decreases at the farm level. Price-transmission studies for milk conducted by Kinnucan and Forker (1987), Carman (1998), Frigon, Doyon, and Romain (1999), Lass, Adanu, and Allen (2001), Carman and Sexton (2005), and Capps and Sherwell (2007) have yielded mixed results regarding the key hypotheses, and each has important limitations. All except Carman and Sexton, and Capps and Sherwell aggregated fluid milk into one product and consequently missed the important differences in pricing based on butterfat content under the alternative forms of competition. Carman and Sexton studied price transmission for skim, 1%, 2%, and whole milk, while Capps and Sherwell focused on 2% and whole milk. However, neither disaggregated the farm price into component costs due to butterfat and nonfat, and each lacked the conceptual foundation provided here to test specific competition hypotheses.

Retail milk pricing in California has itself long been controversial, with claims that supermarket chains engaged in "price gouging" of consumers (Odabashian, 1997a,b). Key complaints among consumer advocates were: (*a*) California retail prices were among the

highest in the nation, despite California being a low-cost producing state; (*b*) price transmission was asymmetric; (*c*) supermarket prices for fluid milk were higher than prices charged by convenience stores; and (*d*) supermarkets did not compete actively for milk sales. California cities were among the western U.S. cities analyzed by Carman and Sexton (2005), but their results were somewhat inconclusive:

> California markets have a number of retail price coefficients for farm price increases and decreases that are consistent with competitive pricing and several that are not.... The monopoly hypothesis that the coefficients are equal to 0.50 was not rejected for two-percent milk in Sacramento and San Francisco, for one-percent milk in San Francisco, and for skim milk in Los Angeles and San Diego (p. 528).

Empirical Methodology and Data

We conducted empirical studies of retail milk markets in the four California cities of Sacramento, San Francisco, San Diego, and Los Angeles, using monthly data from April 1999 through November 2003. Our methodology is based on the price transmission literature. Retailers' costs of selling fluid milk products include wholesale prices paid to processors and their own selling costs. Thus, in addition to the butterfat and nonfat cost factors that are the focus here, retail milk prices may also be affected by factors that shift processing and retailing costs and that affect consumer demand. Accordingly, we specify an econometric model in which retail milk prices are a linear function of the butterfat cost and nonfat cost, and utilize control variables to account for demand and retailer and processor cost shifts.

We used the farm value of skim milk and butterfat to represent C_0 and C_f.[11] California has its own stabilization and marketing program for market milk for both northern and southern California marketing areas. Prior to the beginning of each month, the program sets minimum monthly milk prices and milk component prices for various classes of milk.[12] We obtained the minimum farm prices of Class 1 (fluid milk) skim milk and butterfat (C_0 and C_f, respectively) for northern and southern California from various issues of the *California Dairy Information Bulletin*,[13] and the average monthly retail prices of skim, 1%, 2%, and whole milk for the four California cities.[14] The retail prices were based on AC Nielsen Scantrack Reports for each month. Summary statistics are reported in table 2. Note that there are significant variations in the two cost factors and four retail milk prices.

Data on processing and retail selling costs were not available, so their mean effect is captured in the constant term, and secular changes in the cost variables are captured through a time trend.[15] The main demand-shift variable to consider during the short time series under

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[11] We do not observe the actual prices charged to retailers by processors for the alternative fluid milk products, so use of the farm values for C_0 and C_f presumes that farm cost changes are passed on fully to retailers, as would be true, for example, if processors set prices competetively or if retailers are vertically integrated into milk processing, which Odabashian (1997a) notes is often true for California supermarkets.

[12] The minimum monthly component farm prices for Class 1 milk are calculated using specific formulas, and the Chicago Mercantile Exchange AA butter and block cheddar cheese prices during the period between the 26th day of the second previous month and the 10th day of the previous month and the two most recent weekly price reports for nonfat dry milk f.o.b. California manufacturing plants available on the 10th day of the previous month.

[13] Farmers may receive more than the minimum prices if the processor is able to obtain an over-order premium. Such premiums, if they exist, are not decomposed according to fat and nonfat content of milk, and their magnitudes are not reported.

[14] The retail price for fluid milk products may also vary due to retailers' sales and promotion strategies. One advantage to using price data aggregated to the city level is to average out this type of variability that is unrelated to demand and cost factors.

[15] This approach seems preferable to the main alternative of adding aggregate indices for wages and other input costs to the model to account for retailer and processor costs, as these indices represent imperfect proxies at best for the true costs and would exhibit high collinearity.

Table 2. Summary Statistics for Retail Prices and Milk Costs ($/gallon)

Description	SACRAMENTO Mean (Std. Dev.)	SAN FRANCISCO Mean (Std. Dev.)	SAN DIEGO Mean (Std. Dev.)	LOS ANGELES Mean (Std. Dev.)
Butterfat Cost [a]	1.38 (0.36)	1.38 (0.36)	1.38 (0.36)	1.38 (0.36
Nonfat Cost	0.83 (0.11)	0.83 (0.11)	0.85 (0.11)	0.85 (0.11)
Skim Milk Retail Price	2.28 (0.14)	2.36 (0.15)	2.78 (0.14)	2.76 (0.18)
1% Milk Retail Price	2.76 (0.20)	3.12 (0.23)	2.77 (0.20)	2.82 (0.23)
2% Milk Retail Price	2.60 (0.19)	2.53 (0.18)	2.65 (0.17)	2.70 (0.19)
Whole Milk Retail Price	2.71 (0.23)	2.69 (0.23)	2.77 (0.21)	2.84 (0.21)

[a] The statistics for butterfat cost are measured in $/pound.

analysis was seasonality in demand. The summer months of June, July, and August are the three months with lowest daily milk consumption in California, and this effect was captured with an indicator variable for those months. Gradual shifts in demand (e.g., due to income growth) will be captured in the trend variable.

For the econometric model of retail milk prices within a city, the errors are likely contemporaneously correlated across the four milk price equations because the effects of any factors excluded from the econometric model may be captured in the errors of the price equations. We therefore used the seemingly unrelated regression (SUR) method to jointly estimate milk price equations for a city. The SUR estimation also allows us to conduct joint hypothesis tests to characterize market competition.

Hypotheses

Based on the predictions of the theoretical models, we identified the null hypotheses for each of the three competition scenarios. For the model of perfect competition, we jointly tested eight null hypotheses: $a_0 = 0$, $a_1 = 1$, $a_2 = 2$, $a_3 = 3.5$, $b_0 = 1$, $b_1 = 0.99$, $b_2 = 0.98$, and $b_3 = 0.965$, where a_j and b_j are the empirical effects of the butterfat and nonfat cost, respectively, on the retail price of milk product j in the econometric model. We also separately tested two unique predictions, $a_0 = 0$ and $a_3 = 3.5$, of the perfect competition model regarding impacts of butterfat costs on skim and whole milk prices, respectively, which are different from predictions of the oligopoly and covered-monopoly models.

For the covered-monopoly model, we separately tested four null hypotheses: $a_0 < 0$, $a_2 < 0$, $b_1 < 0$, and $b_3 < 0$, which are the unique conceptual results for this scenario. For the oligopoly model, we separately tested this scenario's two unique null hypotheses, $a_0 > 0$ and $a_3 < 3.5$, regarding transmission of butterfat costs. The theoretical results for the oligopoly model show that transmission of the nonfat costs falls in a narrow value range (0.965, 1), which can be very difficult to test empirically. Thus, we used a joint test of the null

hypotheses that the four price effects of the nonfat cost are within the range (0.965, 1). Specifically, we jointly tested four hypotheses, $b_0 = 0.995$, $b_1 = 0.985$, $b_2 = 0.98$, and $b_3 = 0.97$, whose values are arbitrarily chosen but are consistent with the result from the oligopoly model that $0.965 < \beta_3 < \beta_2 < \beta_1 < \beta_0 < 1$.

Estimation Results and Tests

The estimation results are reported in tables 3 and 4. The model fits the data very well for each city. Most parameter estimates are statistically significant, and the adjusted R^2 statistics are usually very high. The joint hypothesis tests and results are reported in tables 5 and 6. The hypothesis tests for individual coefficients are based on *t*-tests and can be inferred from the coefficient estimates and their significance levels in tables 3 and 4. Results of these tests are also summarized in tables 5 and 6.

Considering the results for northern California first, the test results for Sacramento do not reject any of the null hypotheses of the oligopoly model, but do reject those of perfect competition and covered monopoly. For San Francisco, the results do not reject the two separately tested null hypotheses of the oligopoly scenario ($a_0 > 0$, $a_3 < 3.5$), but do reject the third, jointly tested hypothesis regarding transmission of nonfat costs. The hypotheses of perfect competition and covered monopoly are also rejected. Notably, a change in the butterfat cost has a statistically significant positive effect on the skim milk price in both Sacramento and San Francisco, which is consistent with only the oligopoly model. Thus, results strongly support an oligopoly characterization of the retail milk market in Sacramento, while San Francisco exhibits some, but not all, characteristics of oligopoly.

For the southern California cities of San Diego and Los Angeles, the results also reject the null hypotheses of the covered-monopoly model, but are less conclusive as they pertain to perfect competition. The joint test of perfect competition regarding the a_j and b_j coefficients is rejected for both San Diego and Los Angeles, and for San Diego the hypothesis that $a_0 = 0$ is rejected, but the hypothesis that $a_3 = 3.5$ is not rejected. These results are reversed for Los Angeles: the hypothesis that $a_3 = 3.5$ is rejected, but the hypothesis that $a_0 = 0$ is not rejected. None of the predictions of the oligopoly model are rejected for Los Angeles, while for San Diego the joint hypothesis regarding the b_j coefficients is rejected, but the hypotheses that $a_0 > 0$ and $a_3 < 3.5$ are not rejected.

The results are very robust to alternative specifications of the base model. The model was estimated using year fixed effects in place of the time trend. The conclusions for 25 of the 28 hypothesis tests were unaffected by this change, and exactly half of the 64 coefficients for the year effects were significant, whereas 10 of the 16 coefficients on the time trend were significant. In general, goodness of fit was worse with inclusion of year fixed effects. Given that the dummy variable for the summer months was not significant in most instances, the model was estimated excluding it, but conclusions for 27 of 28 hypotheses were unaffected by this change.

On balance, the test results support an oligopoly characterization of the retail fluid milk markets for the four California cities. Our results are sharper in their characterization of the pricing behavior than those obtained by Carman and Sexton (2005) due to the model's specific predictions for milk prices by fat content under alternative market structures, and they lend some support to the critics who have charged that California milk prices are not set competitively.

Table 3. Estimation Results for Sacramento and San Francisco

	Sacramento				San Francisco			
Variable	Skim Milk	1% Milk	2% Milk	Whole Milk	Skim Milk	1% Milk	2% Milk	Whole Milk
Butterfat Cost (a_j)	0.89***	1.42***	1.28***	2.73***	0.84*	0.55	0.53	2.67***
	(0.26)	(0.45)	(0.44)	(0.38)	(0.29)	(0.65)	(0.48)	(0.50)
Nonfat Cost (b_j)	1.12***	1.17***	0.90***	1.07***	1.14***	1.41***	1.13***	1.36***
	(0.07)	(0.12)	(0.12)	(0.09)	(0.08)	(0.17)	(0.13)	(0.14)
Summer	0.03*	0.02	0.03	0.03*	0.03*	0.08*	0.03	0.07***
	(0.01)	(0.02)	(0.02)	(0.02)	(0.01)	(0.03)	(0.03)	(0.03)
Time Trend	0.004***	0.009***	0.01***	0.01***	0.003***	0.01***	0.007***	0.01***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)	(0.001)	(0.001)
Constant	1.12***	1.36***	1.41***	1.14***	1.24***	1.55***	1.34***	0.93***
	(0.07)	(0.11)	(0.11)	(0.10)	(0.07)	(0.16)	(0.12)	(0.13)
Adjusted R^2	0.94	0.90	0.86	0.95	0.90	0.81	0.81	0.89

Notes: Single and triple asterisks (*, ***) denote significantly different from zero at the 10% and 1% levels, respectively. The dependent variable in each column is the retail price of the corresponding type of milk. Values in parentheses are standard errors.

Table 4. Estimation Results for San Diego and Los Angeles

	San Diego				Los Angeles			
Variable	Skim Milk	1% Milk	2% Milk	Whole Milk	Skim Milk	1% Milk	2% Milk	Whole Milk
Butterfat Cost (a_j)	0.84*	1.55***	1.00*	3.04***	0.30	1.45***	1.38***	2.41***
	(0.48)	(0.59)	(0.44)	(0.57)	(0.62)	(0.48)	(0.40)	(0.44)
Nonfat Cost (b_j)	0.73***	0.96***	0.88***	0.63***	0.82***	0.83***	0.92***	0.79***
	(0.12)	(0.14)	(0.11)	(0.14)	(0.16)	(0.12)	(0.10)	(0.11)
Summer	0.003	−0.02	0.03	−0.02	0.04	0.03	0.02	−0.01
	(0.02)	(0.03)	(0.02)	(0.03)	(0.03)	(0.02)	(0.02)	(0.02)
Time Trend	0.001	0.001	0.001	−0.001	−0.004*	−0.005*	−0.001	0.001
	(0.002)	(0.002)	(0.001)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Constant	2.03***	1.79***	1.78***	1.92***	2.15***	2.09***	1.81***	1.88***
	(0.13)	(0.14)	(0.11)	(0.14)	(0.17)	(0.12)	(0.11)	(0.13)
Adjusted R^2	0.78	0.79	0.85	0.83	0.79	0.92	0.92	0.92

Notes: Single and triple asterisks (*, ***) denote significantly different from zero at the 10% and 1% levels, respectively. The dependent variable in each column is the retail price of the corresponding type of milk. Values in parentheses are standard errors.

Table 5. Hypothesis Tests of Competition Scenarios for Sacramento and San Francisco

Scenarios	Null Hypotheses (H_0)	Test Results	H_0 Conclusions [a]
SACRAMENTO:			
► Perfect Competition	$a_0 = 0$, $a_1 = 1$, $a_2 = 2$, $a_3 = 3.5$, $b_0 = 1$, $b_1 = 0.99$, $b_2 = 0.98$, and $b_3 = 0.965$	χ^2 Statistic = 64.4 Probability = 0.00	Reject
	$a_0 = 0$	†	Reject
	$a_3 = 3.5$	†	Reject
► Covered Monopoly	$a_0 < 0$, $a_2 < 0$, $b_1 < 0$, $b_3 < 0$	†	Reject
► Oligopoly	$b_0 = 0.995$, $b_1 = 0.985$, $b_2 = 0.98$, and $b_3 = 0.97$	χ^2 Statistic = 6.80 Probability = 0.15	Do not reject
	$a_0 > 0$	†	Do not reject
	$a_3 < 3.5$	†	Do not reject
SAN FRANCISCO:			
► Perfect Competition	$a_0 = 0$, $a_1 = 1$, $a_2 = 2$, $a_3 = 3.5$, $b_0 = 1$, $b_1 = 0.99$, $b_2 = 0.98$, and $b_3 = 0.965$	χ^2 Statistic = 47.0 Probability = 0.00	Reject
	$a_0 = 0$	†	Reject
	$a_3 = 3.5$	†	Reject
► Covered Monopoly	$a_0 < 0$, $a_2 < 0$, $b_1 < 0$, $b_3 < 0$	†	Reject
► Oligopoly	$b_0 = 0.995$, $b_1 = 0.985$, $b_2 = 0.98$, and $b_3 = 0.97$	χ^2 Statistic = 12.0 Probability = 0.02	Reject
	$a_0 > 0$	†	Do not reject
	$a_3 < 3.5$	†	Do not reject

Note: The symbol † indicates the results of the separate hypothesis tests can be inferred from the coefficient estimates and their significance levels in table 3 or through a simple *t*-test.
[a] Null hypotheses are rejected at the 10% level.

Extensions[16]

We tested for sensitivity of the results to changes in the empirical model specification to allow for delayed and asymmetric transmission of farm price changes to retail. Given that the data in this study are monthly, delayed transmission should be less of a consideration than for weekly data. We examined adding one- and two-month lagged farm-cost variables to the econometric model. For the empirical model with contemporaneous and one-month lag for the farm-cost variables, 18 of the 32 coefficient estimates for the variables with one-month lags were insignificant at the 0.10 level. We analyzed two further specifications of this model. One included only the 14 statistically significant one-month lagged variables for C_0 and C_f. The other included 24 one-month lagged variables that were chosen based on various standard and more inclusive procedures: adjusted R^2, Akaike information criterion, and Schwarz

[16] All results discussed in this section are available from the authors upon request.

Table 6. Hypothesis Tests of Competition Scenarios for San Diego and Los Angeles

Scenarios	Null Hypotheses (H_0)	Test Results	H_0 Conclusions [a]
SAN DIEGO:			
► Perfect Competition	$a_0 = 0$, $a_1 = 1$, $a_2 = 2$, $a_3 = 3.5$, $b_0 = 1$, $b_1 = 0.99$, $b_2 = 0.98$, and $b_3 = 0.965$	χ^2 Statistic = 38.9 Probability = 0.00	Reject
	$a_0 = 0$	†	Reject
	$a_3 = 3.5$	†	Do not reject
► Covered Monopoly	$a_0 < 0$, $a_2 < 0$, $b_1 < 0$, $b_3 < 0$	†	Reject
► Oligopoly	$b_0 = 0.995$, $b_1 = 0.985$, $b_2 = 0.98$, and $b_3 = 0.97$	χ^2 Statistic = 14.7 Probability = 0.01	Reject
	$a_0 > 0$	†	Do not reject
	$a_3 < 3.5$	†	Do not reject
LOS ANGELES:			
► Perfect Competition	$a_0 = 0$, $a_1 = 1$, $a_2 = 2$, $a_3 = 3.5$, $b_0 = 1$, $b_1 = 0.99$, $b_2 = 0.98$, and $b_3 = 0.965$	χ^2 Statistic = 21.9 Probability = 0.01	Reject
	$a_0 = 0$	†	Do not reject
	$a_3 = 3.5$	†	Reject
► Covered Monopoly	$a_0 < 0$, $a_2 < 0$, $b_1 < 0$, $b_3 < 0$	†	Reject
► Oligopoly	$b_0 = 0.995$, $b_1 = 0.985$, $b_2 = 0.98$, and $b_3 = 0.97$	χ^2 Statistic = 4.31 Probability = 0.37	Do not reject
	$a_0 > 0$	†	Do not reject
	$a_3 < 3.5$	†	Do not reject

Note: The symbol † indicates the results of the separate hypothesis tests can be inferred from the coefficient estimates and their significance levels in table 4 or through a simple *t*-test.
[a] Null hypotheses are rejected at the 10% level.

criterion (Greene, 2000, pp. 306, 717).[17] Inclusion of either the 14 or the 24 one-month lagged variables for C_0 and C_f had little effect on the estimates of the total impact of nonfat and butterfat costs on retail prices of the milk products. With either specification, only the results for three of the 28 hypothesis tests changed—the joint hypothesis and the hypothesis $a_3 = 3.5$ for perfect competition were not rejected for Los Angeles, and one hypothesis for oligopoly was rejected for Sacramento. These new results do not change the base empirical model's conclusion that the retail milk market in Los Angeles exhibits a mix of characteristics of perfect competition and oligopoly, and the retail milk market in Sacramento exhibits characteristics of oligopoly.

When the econometric model was augmented to include two-month lags of the farm-cost variables, 22 of the 32 coefficient estimates for the variables with two-month lags were insignificant. In eight cases with significant two-month lag variables, their inclusion caused

[17] Kinnucan and Forker (1987), Borenstein, Cameron, and Gilbert (1997), and Peltzman (2000) chose lagged variables based on significance levels. Goodwin and Holt (1999) and Chavas and Mehta (2004) used the procedures discussed in Greene (2000).

the corresponding one-month lag variable to become insignificant in six of the instances, leaving only two of 32 instances when both one- and two-month lags were significant.

Our tests of asymmetric price transmission focused on possible asymmetries in magnitude of transmission (instead of asymmetries in speed of adjustment). Li (2007) argues that unit root tests should be used in selecting among a lagged-adjustment model (LAM), partial-adjustment model, or hybrid lagged and partial adjustment model. If retail and farm price series are stationary, then the LAM is preferable. Using augmented Dickey-Fuller tests, we concluded that all retail milk price series and the fat and nonfat cost series do not have a unit root, meaning they are stationary over our data period, supporting use of a LAM.

A LAM similar to the models employed by Chavas and Mehta (2004) and Li (2007) was used to estimate the effects of the cost increases and decreases (current and lag terms) of butterfat and nonfat costs on retail prices, and those results were used to conduct tests of the null hypotheses that cost increases and decreases have symmetric effects on the retail prices. The test results do not reject the null hypothesis of symmetric impacts for 49 (77%) of 64 tests. Therefore, for the California markets during the time period of our study, asymmetric transmission of changes in butterfat and nonfat costs to retail prices was not an important issue.

Conclusion

This paper has studied retail pricing of fluid milk products using a new theory of pricing for products that are horizontally differentiated from the perspective of consumers' preference ranking but exhibit differential costs of production. Pricing behavior was studied under three competition settings: perfect competition, covered monopoly, and oligopoly. All variable costs are fully transmitted to retail under the benchmark setting of perfect competition. However, a number of interesting results emerge under covered monopoly and oligopoly pricing, which are distinct from the predictions of standard market-power models. For example, an increase in the butterfat cost leads to a larger cost difference among fluid milk products, reducing the skim milk price in a monopoly setting, and increasing it in an oligopoly market, even though skim milk contains no butterfat, and hence its price would be unaffected under perfect competition. The 2% milk price is also reduced by an increase in the butterfat cost in the covered-monopoly scenario. Further, the model yields new insights on the important and controversial question of price transmission for milk. For example, in oligopoly the model predicts that nonfat costs are transmitted in excess of 100% for whole milk, but butterfat costs are only partially transmitted.

An empirical study of the effects of the cost factors on retail milk prices was conducted for four California cities during the period 1999–2003, and the results were utilized to characterize competition in those retail milk markets. The oligopoly scenario was supported by the estimation results for the retail milk markets in Sacramento and San Francisco, while the results for the markets in San Diego and Los Angeles demonstrated a mix of characteristics of perfect competition and oligopoly.

We believe the model of multiproduct pricing developed here in the context of retail pricing of fluid milk products has the potential to be applied in other settings, both for food and nonfood products, when sellers can exercise market power. The model extends readily to more or fewer product categories than the four fluid milk products considered here. However, future research should also consider the problem of optimal product selection for markets with horizontally differentiated products with differential costs.

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Appendix:
The Coefficients in the Oligopoly Scenario

The coefficients in the equilibrium price functions in the oligopoly scenario are functions of model parameters. The functions are as follows:

$$\delta_0 = \delta_3 = \left(g_{11} + 2g_{00} - 2h_{00}\right)/\Phi,$$

$$\delta_1 = \delta_2 = \left(3g_{00} + g_{01} - 2h_{00}\right)/\Phi,$$

$$\alpha_0 = \left[\left(g_{11} + 3g_{00} + g_{01} - 3h_{00}\right) + \left(g_{00} - g_{01}\right)\left(g_{00} + g_{01} - h_{00}\right)^2/2\Phi\right]\left(g_{00} - h_{00}\right)/\Psi,$$

$$\alpha_1 = 1 + \left[\left(g_{00} - h_{00}\right)/\Psi\right]\left[g_{00} + g_{01} - h_{00} + \left(g_{00} - g_{01}\right)\left(2g_{00} - h_{00}\right)\left(g_{00} + g_{01} - h_{00}\right)/2\Phi\right],$$

$$\alpha_2 = 2 - \left[\left(g_{00} - h_{00}\right)/\Psi\right] \times$$
$$\left[g_{00} + g_{01} - h_{00} - \left(g_{00} - g_{01}\right)\left[\left(2g_{00} - h_{00}\right)\left(g_{11} + 2g_{00} - 2h_{00}\right) - \left(g_{00} + g_{01} - h_{00}\right)^2\right]/2\Phi\right],$$

$$\alpha_3 = 2 + 3g_{00}/\left(4g_{00} - 2h_{00}\right) - \left(g_{00} - h_{00}\right)\left(g_{00} + g_{01} - h_{00}\right)\left[\Psi\left(2g_{00} - h_{00}\right)\right]^{-1} \times$$
$$\left[g_{00} + g_{01} - h_{00} - \left(g_{00} - g_{01}\right)\left[\left(2g_{00} - h_{00}\right)\left(g_{11} + 2g_{00} - 2h_{00}\right) - \left(g_{00} + g_{01} - h_{00}\right)^2\right]/2\Phi\right],$$

and

$$\beta_j = 1 - 0.01\alpha_j \text{ for } j = 0, 1, 2, 3,$$

where

$$\Phi = \left[\left(g_{00} - g_{01}\right)\left(g_{00} + g_{01} - h_{00}\right) + \left(g_{11} - 2g_{01}\right)\left(2g_{00} - h_{00}\right)\right]$$

and

$$\Psi = \left[\left(g_{00} - g_{01}\right)\left(g_{00} + g_{01} - h_{00}\right) + \left(g_{11} + 2g_{00} - 2h_{00}\right)\left(2g_{00} - h_{00}\right)\right].$$