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## Intertemporal price discrimination in storable goods markets

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THE CENTER FOR THE STUDY  
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Intertemporal Price Discrimination  
in Storable Goods Markets

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April 18, 2011

# Intertemporal Price Discrimination in Storable Goods Markets\*

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## Abstract

We study intertemporal price discrimination when consumers can store for future consumption needs. To make the problem tractable we offer a simple model of demand dynamics, which we estimate using market level data. Optimal pricing involves temporary price reductions that enable sellers to discriminate between price sensitive consumers, who anticipate future needs, and less price-sensitive consumers. We empirically quantify the impact of intertemporal price discrimination on profits and welfare. We find that sales: (1) capture 25-30% of the profit gap between non-discriminatory and third degree price discrimination profits, and (2) increase total welfare.

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# 1 Introduction

Consumers are heterogeneous in many ways including preferences, income, transportation cost and storage costs. Consumer heterogeneity generates incentives for firms to price discriminate. When consumer types are unobservable firms rely on various screening mechanisms to achieve separation. Empirically, we know little about the potential benefits from price discrimination in actual settings, or how well various screening mechanisms work. Furthermore, the impact of price discrimination on welfare, especially in an oligopoly setting, is theoretically unclear.

The goal of this paper is to empirically study the role of intertemporal price discrimination in storable goods markets. In these markets, temporary price reductions (sales) can be a way to separate between consumers based on their ability to store. We estimate preferences, and use the estimates to test whether sales can be driven by price discrimination. Next, we evaluate the effectiveness of sales as a price discriminating tool relative to third-degree discrimination, where the seller can identify the different consumer types and prevent arbitrage. Finally, we assess the consequences of discrimination on consumer and total welfare.

In order to address these issues we need a model of pricing that is workable and consistent with demand dynamics. A key computational and conceptual challenge in modelling the sellers' problem is the size of the state space. It is not clear how to reasonably model the complex problem sellers face. Sellers' profits, in principle, depend on the inventory of each potential buyer. In which case, not only modeling the seller problem becomes very complex, but also it is unreasonable to assume the seller can access and process such detailed information. One could imagine solving the seller's problem by assuming some sort of rule of thumb or approximation to the optimal behavior. We explore an alternative which relies on a simple dynamic demand model. The simplicity of the model helps in two ways. First, demand is easy to estimate using market level data and computationally no more costly than static demand estimation. Second, the proposed demand framework leads to a simple solution to the sellers' pricing problem. The model provides a clear delineation of what sellers must observe to solve their problem, and makes the problem tractable.

The simplicity of the demand model is due to the storage technology: consumers store for a pre-specified maximum number of periods. Characterizing consumer behavior does not require solving the value function. The problem remains dynamic, but easy to solve. The model is flexible enough to accommodate product differentiation, consumer heterogeneity and endogenous consumption, while allowing for storability.

We estimate the demand model using store level scanner data for soft drinks and find that consumers who store are more price sensitive than consumers who do not. This suggests that firms would benefit from separating these groups, targeting storers with lower

prices. To evaluate profits and consumer surplus under different pricing regimes we use the estimated demand, and respective first order conditions. Two benchmarks are considered. One benchmark is non-discriminatory pricing. The other benchmark is third degree price discrimination under the assumption of no arbitrage, namely, assuming sellers can target different populations. Profits under third degree discrimination are a non-feasible upper bound on gains from price discrimination. The target is not feasible because in practice sellers cannot perfectly separate the different buyer types. We find that third degree price discrimination would increase profits by 9-14% relative to non-discriminatory prices. Sales, as a form of partial discrimination, enable sellers to capture around 24-30% of the potential additional profits generated from discrimination.

The welfare implications of third degree price discrimination by a monopolist were studied by Robinson (1933), and later formalized by Schmalensee (1981), Varian (1984) and Aguirre et al. (2010) among others. The impact of discrimination on welfare is ambiguous. In oligopoly situations there are virtually no (theoretical) welfare results. Therefore examining the issues empirically is of particular interest. We find that total welfare increases. Sellers are better off as are consumers who store. Consumers who do not store are worse off, but in most cases their loss is more than offset by storers' welfare gains.

Besides quantifying the impact of price discrimination there are other reasons to be interested in our supply side analysis. There is a long tradition in Industrial Organization of using demand estimates in conjunction with static first order conditions to infer market power. Demand dynamics render static first order conditions irrelevant. A supply framework consistent with demand dynamics is needed to infer market power. In addition, Macro and Trade economists are interested in studying the pass through of exchange rates and monetary shocks to consumer prices. To fully understand disaggregate micro level patterns one needs a supply model that can be used to simulate the pass through.

Our paper is related to several strands in the literature. Numerous papers in Economics and Marketing document demand dynamics, specifically, demand accumulation (see Blatberg and Neslin (1990) for a survey of the Marketing literature). Boizot et al. (2001) and Pesendorfer (2002) show that demand increases in the duration from previous sales. Hendel and Nevo (2006a) document demand accumulation and demand anticipation effects, namely, duration from previous purchase is shorter during sales, while duration to following purchase is longer for sale periods. Erdem, Imai and Keane (2003), and Hendel and Nevo (2006b) estimate structural models of consumer inventory behavior. Our demand model is motivated by this literature but offers substantial computational savings and a tractable supply analysis.

Several explanations have been proposed in the literature to why sellers offer temporary discounts. Varian (1980) and Salop and Stiglitz (1982) propose search based explanations which deliver mixed strategy equilibria, interpreted as sales. Sobel (1984), Conlisk Gerstner

and Sobel (1984), and Pesendorfer (2002) present models of intertemporal price discrimination in the context of a durable good (more recently used by Chevalier and Kashyap (2011)), while Narasimhan and Jeuland (1985) and Hong, McAfee and Nayyar (2002) do so for storable goods.

Our estimates show that sellers have an incentive to intertemporally price discriminate, suggesting that sales are probably driven by discrimination motives. Incentives for sales are similar to Narasimhan and Jeuland (1985) and Hong, McAfee and Nayyar (2002) but in a somewhat different context. Hong et al. model an homogenous good sold in different stores, under unit demand, and single unit storage. Since the interest in this paper is empirical we need a framework amenable for demand estimation, that allows for product differentiation and endogenous consumption and storage levels, depending on prices.

The abovementioned third-degree discrimination theoretical results (e.g., Robinson (1933), Schmalensee (1981), and Aguirre et al. (2010)) apply to the intertemporal discrimination in our model, once we reinterpret demand during sale periods –following Robinson’s terminology– as the weak demand, and demand during non-sale periods as the strong demand.

Finally, our results relate to several papers in the empirical price discrimination literature. Shepard (1991) finds that, consistent with price discrimination motives, the price gap between full and self service is higher at gas stations offering both levels of service relative to the average difference between prices at stations offering only one type of service. Verboven (1996) considers whether discrimination can explain differences in automobile prices across European countries. Villas-Boas (2009) uses demand estimates and pricing (in the vertical chain) to predict that banning wholesale price discrimination in the German coffee market would increase welfare.

The paper proceeds as follows. In the next subsection we presents some motivating facts. Section 2 presents a general, but non practical, model of demand and supply followed by our simple model. Section 3 presents the estimation. Section 4 presents the application to soft drinks.

## 1.1 Motivating Facts

Figure 1 shows the price of a 2-liter bottle of Coke in a store over a year. The pattern is typical of pricing observed in scanner data: regular prices and occasional sales, with return to the regular price. With the exceptions of a short transition period, in any given 2-3 week window there are two relevant prices: a sale price and a non-sale price. We note that while sales are not perfectly predictable they are quite regular and frequent. Both these facts will feed into our modeling below.

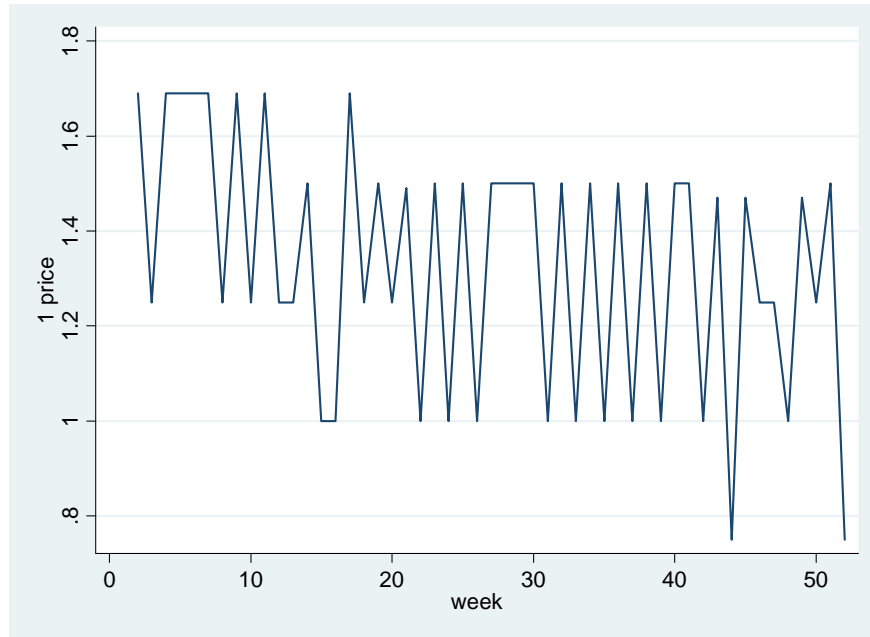


Figure 1: A typical pricing pattern

Note: The figure presents the price of a 2-liter bottle of Coke over 52 weeks in one store.

The pattern in Figure 1 raises two immediate questions: how do consumers faced with this price process behave? And what is the supply model that generates this pattern?

Since soft-drinks are storable, pricing like this creates incentives to anticipate future needs: buy during a sale for future consumption. Indeed, quantity purchased shows evidence of demand anticipation. Table 1 displays the quantity of 2-liter bottles of Coke sold during sale and non-sale periods (we present the data in more detail later). During sales the quantity sold is significantly higher (623 versus 227, or 2.75 times more). More importantly, the quantity sold is lower if a sale was held in the previous week (399 versus 465, or 15 percent lower). The impact of previous sales is even larger if we condition on whether or not there is a sale in the current period (532 versus 763, or 30 percent lower, if there is a sale and 199 versus 248, or 20 percent lower in non sale periods).

We interpret the simple patterns present in Table 1 as evidence of demand dynamics and that consumers' ability to store detaches consumption from purchases. Table 1 shows that purchases are linked to previous purchases, or at least, to previous prices. Moreover, Table 1 hints that storing behavior might be heterogeneous. If every consumer stored during sales we would expect quantity sold at non-sale price that follows a sale to be quite small. The first row shows that is not the case.

Table 1: Quantity of 2-Liter Bottles of Coke Sold

	$S_{t-1} = 0$	$S_{t-1} = 1$	
$S_t = 0$	247.8	199.4	227.0
$S_t = 1$	763.4	531.9	622.6
	465.0	398.9	

Note: The table presents the average across 52 weeks and 729 stores of the number of 2-liter bottles of Coke sold during each week. As motivated in the text, a sale is defined as any price below 1 dollar.

We now turn to the second question: what supply model generates such a pricing pattern? The literature has offered several explanations. First, in principle the sales pattern could be driven by changes in costs or demand. In practice, its hard to imagine changes in static conditions that would generate this pricing pattern.

An alternative explanation focuses on consumer search behavior. Varian (1980) and Salop and Stiglitz (1982) offer a model where in equilibrium firms pricing involves mixed strategies and price reductions. While these models have some attractive features, like their ability to generate random sales, they also yield some predictions that are hard to match with the data (like a continuous price support).

A third theory explains sales as part of retailer behavior and multi-category pricing (Lal and Matutes, 1994). In these models price reductions are seen as loss leaders and meant to draw consumers in to the store.

A final set of theories focus on sales as intertemporal price discrimination (Sobel, 1984; Conlisk, Gerstner and Sobel, 1984; Pesendorfer, 2002; Narasimhan and Jeuland, 1985; Hong, McAfee and Nayyar, 2002). We focus on this class of models and test whether consumer preferences and storing ability can explain sales in this market. Finding that it can, we quantify the impact of sales.

## 2 The Model

In order to evaluate the impact of intertemporal price discrimination we need to compute equilibrium prices. We start by presenting a general model of demand and supply for storable goods and discuss the difficulties in solving the model. In setting up the general model, the goal is to highlight not only the computational savings of the simple model we propose, but also the conceptual problems that arise in the general set up that need to be resolved. We then propose a simple demand model, derive its predictions and its implications for seller behavior.



## 2.1 Demand and Supply with Storable Products

Assume consumer  $h$  has preferences at time  $t$  given by a utility function  $U(\mathbf{q}, m; \theta_{ht})$ , where  $\mathbf{q} = [q_1, q_2, \dots, q_J]'$  is the vector of quantities consumed of the  $J$  varieties of the product,  $m$ , is the quantity consumed of a numeraire, and  $\theta_{ht}$  is a vector of consumer specific time varying parameters. We denote  $U_{ht}(\mathbf{q}, m) \equiv U(\mathbf{q}, m; \theta_{ht})$ . Consumers can store for future consumption at costs  $C_h(\mathbf{i})$ , where  $\mathbf{i}$  is a vector of dimension  $J$  of the inventory of all brands. Consumers know current prices and the distribution of prices at period  $t+1$ ,  $F(\mathbf{p}|H_t)$ , where  $\mathbf{p}$  is a vector of dimension  $J$  of prices and  $H_t$  is the history up to  $t$ .

The consumer's problem in each period  $t$  is to choose purchases,  $\mathbf{x}_t$ , and consumption,  $\mathbf{q}_t$  of each brand to

$$\begin{aligned} & \text{Max} \sum_{\tau=0}^{\infty} \beta_h^\tau \mathbb{E} [U_{h_{t+\tau}}(\mathbf{q}_{t+\tau}, m_{t+\tau}) - C_h(\mathbf{i}_{t+\tau}) | H_t] \\ & \text{s.t. } \mathbf{p}'_{t+\tau} \mathbf{x}_{t+\tau} + m_{t+\tau} \leq y_{t+\tau} \quad \text{and} \quad \mathbf{i}_{t+\tau} = \mathbf{i}_{t+\tau-1} + \mathbf{x}_{t+\tau} - \mathbf{q}_{t+\tau} \end{aligned} \quad (1)$$

where  $\beta_h$  is the discount factor, and  $y_t$  is the consumer's income at period  $t$ . The expectation is taken with respect to future prices as well as uncertain future needs. Consumers trade off purchasing today, if prices are low, and paying a storage cost. Market demand,  $\mathbf{X}_t(\mathbf{p}_t, H_t)$ , is given by aggregation across consumers who solve the problem in equation (1).

The seller's problem is to choose a series of prices to maximize the discounted flow of expected profits,  $\pi(\cdot)$ . For simplicity, we assume the seller is a monopolist who can commit to future prices, and produces all varieties at a constant marginal cost,  $c$ . Then the seller's problem is to choose prices,  $\mathbf{p}_t$ , to maximize

$$\sum_{\tau=0}^{\infty} \delta^\tau \mathbb{E} [\pi(\mathbf{p}_{t+\tau}) | H_t] = \sum_{\tau=0}^{\infty} \delta^\tau \mathbb{E} [(\mathbf{p}_{t+\tau} - \mathbf{c}_{t+\tau})' \mathbf{X}_{t+\tau}(\mathbf{p}_{t+\tau}, H_{t+\tau}) | H_t]. \quad (2)$$

The expectation is taken with respect to future demand shocks that impact both the functional form of  $\mathbf{X}_{t+\tau}$  and the history in future periods,  $H_{t+\tau}$ . Note, that if demand is static,  $\mathbf{X}_t(\mathbf{p}_t, H_t) = \mathbf{X}_t(\mathbf{p}_t)$ , then the pricing problem is static.

### 2.1.1 Equilibrium and the Information Structure

The equilibrium prices are determined by the interaction between the problems outlined in equations (1) and (2). Regardless of what is computationally feasible we would like to discuss what information can be reasonably assumed to be available and likely to be used. What do players' strategies depend on in these markets?

Pricing, in principle, may depend on the inventory held by each of the buyers in the population as well as their preference shocks. Given pricing, consumers purchasing decisions would depend on such information as well, should it be available to them. However, inventories, which depend on previous consumption, are private information. Past purchases could be used to infer individual preference, and perhaps to estimate the current inventory holdings of each buyer. While some individual information might be available for customers that use loyalty cards, the informational and computational burden of processing such information seems enormous. Therefore, it is unreasonable to assume that firms condition on this information. Unable to track individual purchases over time, sellers might still find it useful to condition pricing on the distribution of past quantities sold or, as a proxy, on total quantity sold. However, it raises the issue of whether buyers and competitors have access to such information.

A more realistic assumption is that strategies depend on public information, namely, prices. Hong, McAfee and Nayar (2002) provide a model in which (observable) past prices suffice to infer past purchases. In their model preferences are deterministic and identical, the distribution of holdings can be inferred from purchases. Thus, the starting inventory and the identity of those holding inventory is known at any point in time. With the empirical goal in mind of estimating preferences, we would like a more general model, than Hong et al., that allows for: 1) differentiated products, 2) consumption and the quantity stored to depend on price and 3) non-deterministic demand.

## 2.2 A Simple Demand Model

In this section we propose a model that accommodates the empirical requirements, yet prices are a sufficient statistic for the state. Although simple, it delivers an empirical framework for estimation. We first present the main assumptions, and then discuss the implied purchasing patterns.

### 2.2.1 The Setup

First, we assume that there is heterogeneity in the willingness or ability to store.

**Assumption A1:** a proportion of consumers do not store.

In the setup of Section 2.1 this would arise endogenously if a fraction of the consumers have storage costs that make it unprofitable to store. Therefore, one can view A1 as an assumption on the distribution of storage costs.

We allow storers and non-storers to have different preferences. Let  $U_t^S(\mathbf{q}, m)$  and  $U_t^{NS}(\mathbf{q}, m)$  be the preferences of the representative storing and non-storing consumer, respectively. For

simplicity we assume preferences are quasi-linear, i.e.,

$$U_t^S(\mathbf{q}, m) = u_t^S(\mathbf{q}) + m \quad \text{and} \quad U_t^{NS}(\mathbf{q}, m) = u_t^{NS}(\mathbf{q}) + m. \quad (3)$$

We index preferences by  $t$  to allow for changing demand; we assume that consumers know needs at least  $T$  periods in advance. Preferences could reflect an aggregate consumer, assuming the household level preferences are of Gorman form and yield an aggregate consumer. Alternatively, preferences could represent explicit aggregation over individual households (for example, as in Berry, Levinsohn and Pakes, 1995).

Preference heterogeneity will be an important determinant of seller behavior. It is an empirical matter if, and how, preferences of the types differ. We can, in principle, find that the proportion of either type is zero or that preferences are identical.

Absent storage, purchases equal consumption, thus, consumers' aggregate demand by type is

$$\mathbf{q}_t^S = Q_t^S(\mathbf{p}_t) \quad \text{and} \quad \mathbf{q}_t^{NS} = Q_t^{NS}(\mathbf{p}_t). \quad (4)$$

where  $Q_t(\cdot)$  is the demand function implied by maximizing the utility in (3).

With storage, purchases and consumption need not coincide. In order to predict storers' purchases we make the following assumptions:

**A2 (storage technology):** storage is free, but inventory lasts for only  $T$  periods (fully depreciates afterwards).

Taken literally the assumption implies perishability. For example,  $T = 1$  fits products that would not last more than two weeks (the period of purchase and the following). For products with longer life a higher  $T$  would fit. An alternative interpretation of the assumption is contemplation; while the product may last longer, at the store the buyers only considers purchasing for  $T$  periods ahead. The assumption implies simple dynamics. In the inventory problem defined in Section 2.1, the consumer and the researcher need to keep track of how much is left in storage in different states. As shown in the next section this is not the case here. In addition, the assumption detaches the storage decision of different products. In the problem in Section 2.1 the storage cost is a function of the inventory of all varieties. Under A2 effective prices, of the other products, are a sufficient statistic for quantity in storage. Effective prices, defined later, are the opportunity cost of period  $t$  consumption. Moreover, effective prices are public information. Thus, the assumption not only eases demand estimation but also helps formulate the sellers' problem.

Finally, we assume the following about prices expectations.

**A3 (perfect foresight):** consumers have perfect foresight regarding prices  $T$  periods ahead.

As we will see below with perfect foresight the consumer problem becomes particularly simple. One may worry that perfect foresight is restrictive, thus, invalidating demand estimates and perhaps an inadequate assumption to study sellers behavior. It turns out the perfect foresight assumption fits the supply model under seller commitment. However, we will also consider an alternative assumption:

**A3' (rational expectations):** consumers hold rational expectations about future prices.

We can solve the model under either perfect foresight (A3) or rational expectations (A3') for low  $T$ . We present estimates under both assumptions. For low  $T$ , the results are similar.<sup>1</sup> It is much easier to allow for  $T > 1$  under A3.

### 2.2.2 Purchasing Patterns

We now derive the purchasing patterns implied by A1-A3. For ease of exposition we ignore discounting. The application involves weekly data, and therefore discounting does not play a big role. In order to insure a solution to the dynamic problem we focus on a finite horizon, up to period  $R$ .

Aggregate purchases are the sum of the purchases of the two types of consumers:

$$X_{jt}(\mathbf{p}_{t-T}, \dots, \mathbf{p}_{t+T}) = Q_{jt}^{NS}(\mathbf{p}_t) + X_{jt}^S(\mathbf{p}_{t-T}, \dots, \mathbf{p}_{t+T}) \quad (5)$$

where  $X_{jt}^S(\mathbf{p})$  are purchases by storers. Non-storers behave according to (4).

Storers' purchasing patterns are determined as follows. Their objective function is to maximize the sum of utility in the  $R$  periods subject to a budget constraint and the storing constraints. Formally, they solve

$$\begin{aligned} & \text{Max} \sum_{t=0}^R \mathbb{E}(u_t^S(\mathbf{q}_t) + m_t) \quad \text{subject to} \\ & \sum_{t=0}^R (\mathbf{p}'_t \mathbf{x}_t + m_t) \leq \sum_{t=0}^R y_t \quad \text{and} \quad \mathbf{q}_t \leq \mathbf{x}_t - \sum_{\tau=0}^{t-1} (\mathbf{x}_\tau - \mathbf{q}_\tau - \mathbf{e}_\tau) \end{aligned}$$

where  $\mathbf{x}_t$  is the vector of purchases, and  $\mathbf{e}_\tau$  is the vector of unused units that expire in period  $\tau$ . We have in mind items on which expenses are small relative to wealth  $W$ , so that  $m_t > 0$  for all  $t$ , therefore income effects or liquidity constraints in any particular period do not play a role.

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<sup>1</sup>We believe the reason estimates are similar is that there are well defined sales and non-sale prices. If consumers do not know future prices, but there are two clear price ranges then they purchase for storage on sale, and never store at non-sale prices. In other words, under the two price range assumption knowledge of future prices is not needed to generate the same storing behavior that arises under perfect foresight. Although in the application there are more than two prices, in Figure 1 one can see a clear distinction between sale and non-sale prices.

Assumptions A2 and A3 imply that storers' solve for consumption  $T$  periods in advance. Storage allows them to buy each product consumed at  $t$  at the lowest of the preceding  $T$  prices. To write down the problem, we define the *effective price* of product  $j$  in period  $t$  as

$$p_{jt}^{ef} = \min\{p_{jt}, \dots, p_{jt-\tau}\} \quad (6)$$

where  $\tau = \min\{T, t\}$  is the number of periods back in which period  $t$  consumption could have been purchased. The constraint  $\tau \leq t$  (in the definition of  $\tau$ ) takes care of the initial periods, namely, purchases before period 0 are not feasible.

Using  $\mathbf{p}_t^{ef}$ , which denotes the vector of period  $t$  effective prices, the problem of the storing consumer becomes

$$\text{Max} \sum_{t=0}^R \mathbb{E}(u_t^S(\mathbf{q}_t) + m_t) \quad \text{subject to} \quad (\mathbf{p}_t^{ef} \cdot \mathbf{q}_t + m_t) \leq y_t.$$

The optimization of the storer is a sequence of static optimization problems solved  $T$  periods in advance, and replacing prices by effective prices. Optimal consumption in period  $t$  is  $\mathbf{q}_t^S = Q_t^S(\mathbf{p}_t^{ef})$ . The dynamics are taken care simply by replacing prices by effective prices.

The storage of a product affects the purchases and consumption of all other products exclusively through its effective price. To see that suppose product  $j$  was purchased during a sale for consumption in subsequent periods. Demand for all other products is naturally affected by the fact that product  $j$  is in the pantry waiting to be consumed. How do inventoried units of  $j$  affect demand for  $-j$ ? Since  $p_{jt}^{ef}$  was known at the time of purchasing all varieties to be consumed at period  $t$ , the impact is fully captured by plugging the effective price of consuming  $j$  in those later periods.

Having solved the optimal consumption path we need to predict purchases. In period  $t$  the consumer might purchase for  $t$  as well as for some or all of the following  $T$  periods. For  $r = 0, \dots, T$  purchases at time  $t$  for consumption at time  $t + r$  equal either 0, if  $p_{jt} > p_{jt+r}^{ef}$ , or (absent ties in effective prices)  $Q_{t+r}^S(\mathbf{p}_{t+r}^{ef})$ , if  $p_{jt} = p_{jt+r}^{ef}$ .

However, since prices may repeat themselves between periods  $t - T$  and  $t$  consumers are indifferent when to purchase. We break the tie by assuming that buyers purchase immediately when the price is below a threshold,  $p_j^m$ , and wait otherwise. Namely, for  $p_{jt}^{ef} < p_j^m$  consumers buy right away, while for  $p_{jt}^{ef} \geq p_j^m$  consumers buy in the last opportunity in which prices equal  $p_{jt}^{ef}$ . Threshold  $p_j^m$  triggers action. A possible rationale for this –arbitrary– tie-breaking rule is a little uncertainty about either going to the store or about future prices. As a practical matter we can use median price as the threshold.

The tie breaking rule requires a little more notation. Define  $t^f = \min\{\arg \min_{\tau \leq T}\{\mathbf{p}_{jt}, \dots, \mathbf{p}_{jt-\tau}\}\}$  and  $t^l = \max\{\arg \min_{\tau \leq T}\{\mathbf{p}_{jt}, \dots, \mathbf{p}_{jt-\tau}\}\}$ . These are the first and last time  $p_{jt}^{ef}$  is charged in the  $t - T$  to  $T$  period, respectively.

Period  $t$  purchases are:

$$X_{jt}^S(\mathbf{p}_{t-T}, \dots, \mathbf{p}_{t+T}) = \sum_{r=0}^T Q_{jt+r}^S(p_{jt}, \mathbf{p}_{-j,t+r}^{ef}) \mathbf{1}\{((t = t^f) \cap (p_{jt} < p_j^m)) \cup ((t = t^l) \cap (p_{jt} \geq p_j^m))\} \quad (7)$$

where  $Q_{jt+r}^S(\cdot)$  is static demand defined by (4). The indicator function takes care of two requirements. First, we only want to purchase at time  $t$  for consumption in period  $t + r$  if  $p_{jt} = p_{jt+r}^{ef}$ , that is, if price  $t$  is as good as any other price between  $t + r - T$  and  $t + r$ . Second, the indicator takes care of breaking ties. Purchases take place at  $t$  only if  $t$  is the first event in which a price below the threshold is offered, or the last, if the price is above the threshold.

### 2.2.3 Predicted Behavior for $T=1$

We now spell out what equation (7) implies in the case of  $T = 1$ . Focusing on  $T = 1$ , while just a private case, serves two purposes. First, it will help clarify our estimating equations, highlighting how the model is identified from the data. Second, it prepares the ground to show how the model works under rational expectations.

Equation (7) dictates when consumers buy for future consumption, in this case for  $t + 1$ . We will denote a period as either a non-sale period,  $N$ , or a sale period,  $S$ . Sale periods are periods in which the storing consumer buys for future consumption, that is for product  $j$  period  $t$ , when  $p_{j,t} < p_{j,t+1}$ . A non-sale period,  $N$ , is one which  $p_{j,t} > p_{j,t+1}$ . If  $p_{j,t} = p_{j,t+1}$  then the period is classified as a sale if  $p_{j,t} < p_j^m$  and non sale otherwise.

Consumers who store, purchase for storage at  $S$ , and never store at  $N$ . When they store, they do so for one period, and their purchases are dictated by (4). Thus, to predict consumer behavior we only need to define 4 events (or types of periods): a sale preceded by a sale ( $SS$ ), a sale preceded by a non-sale ( $NS$ ), a non-sale preceded by a sale ( $SN$ ), and two non-sale periods ( $NN$ ).

Assume for a second that only product  $j$  can be stored. Given assumptions A1-A3 storers' purchases at time  $t$  are given by

$$x_{jt}^S(\mathbf{p}_{t-1}, \mathbf{p}_t, \mathbf{p}_{t+1}) = \begin{cases} Q_{jt}^S(p_{jt}, p_{-jt}) & 0 & NN \\ 0 & 0 & SN \\ Q_{jt}^S(p_{jt}, p_{-jt}) & Q_{j,t+1}^S(p_{jt}, p_{-j,t+1}) & NS \\ 0 & Q_{j,t+1}^S(p_{jt}, p_{-j,t+1}) & SS \end{cases} \quad \text{in} \quad (8)$$

where  $Q_{jt}^S()$  is the static demand of storers (defined in (4)).

At high prices there are no incentives to store, in which case purchases equal either: consumption, given by  $Q^S()$ , or zero, if there was a sale in the previous period (i.e., in  $SN$  consumption is out of storage). During sales preceded by a non-sale period purchases are for current consumption as well as for inventory. During periods of sale preceded by a sale, current consumption comes from stored units, so purchases are for future consumption only, and the purchases equal  $Q_{jt+1}^S(p_{jt}, p_{-jt+1})$ . Notice the difference in the second argument of the anticipated purchases relative to purchases for current consumption (e.g.,  $SS$  vs  $NN$ ). Purchases for future consumption take into account the expected consumption of products  $-j$ .

When all products are storable accounting for storability is immediate. The way to incorporate the dynamics dictated by storage is to consider the effective cost (or price) of consumption, which does not necessarily coincide with current price. In other words, if  $-j$  is purchased on sale for future consumption, its effective future price,  $p_{-j,t+1}^{ef}$ , is its current (sale) price since the product will be stored today for consumption tomorrow. For example, consider the event  $NN$  (product  $j$  is not on sale at  $t$  nor at  $t - 1$ ) and assume that product  $-j$  was on sale at  $t - 1$  (but is not on sale at  $t$ ). The demand from consumers who stored is  $Q_{jt}^S(p_{jt}, p_{-jt}^{ef})$  instead of  $Q_{jt}^S(p_{jt}, p_{-jt})$ . A similar adjustment is needed in every state, to account for consumption out of storage.

There are two important implications of equation (8) for estimation. First, when we estimate the model we will use the states to scale demand up or down, but as equation (8) suggests we will use the actual prices for estimation. The definition of the  $N$  and  $S$  is used to define the state not to modify prices: prices are not restricted to take on two values and can take on any value

Second, we can see from equation (8) that contemporaneous prices of other products are the wrong control in the estimation. Controlling for current price generates a bias in the estimated cross price effect. In an inventory model, the effective or shadow price is a complicated creature that requires solving the value function. In our framework, for  $T = 1$ , effective prices are just the minimum of current and previous prices.

Allowing for larger  $T$  in the estimation is immediate. Equation (8) requires adjustment to reflect that consumers can anticipate for longer periods ahead, as reflected in (7), basically rescaling up in case of anticipated purchases, and rescaling demand down, in case of consumption out of storage. Moreover, effective prices are the minimum of the previous  $T$  periods. Basically, period  $t$  consumption is the static demand based on  $\mathbf{p}_t^{ef}$ , while purchases take place at the time the effective price is charged.

## 2.2.4 Rational Expectations

We now explore demand under A3', of rational expectations, while continuing to assume A1 and A2. We will also focus on the  $T = 1$  case. Under these assumptions equation (5) is still valid in the single product case (i.e., if other products are either not present or are sold at a constant price) but we need an appropriate classification of  $N$  and  $S$  periods.

Naturally, we cannot define a sale based on  $t + 1$  prices, which are not yet known (absent perfect foresight). Given the distribution of future prices, as shown in Hong et al. (2002) and Perrone (2010), there is a threshold below which the good is purchased for future consumption. We thus define sale and non-sale periods based on the price thresholds.

We will classify the periods of high prices as non-sale and low prices as sales. At high prices buyers do not have an incentive to store, denote them as  $N$  periods. During a sale period,  $S$ , consumers have an incentive to store, even if some sales are deeper than others. Thus, rational expectations and unrestricted price support work fine in the single product case.<sup>2</sup>

When more than one product is storable the analysis involves the following issue. At the time of purchasing product  $j$  the (effective) prices of other products may not be known. They would be known, for example, if the other products are on sale, in which case the effective price is the current sale price. In general, when some other products are not on sale, the consumer has to purchase product  $j$  under uncertain  $-j$  prices. Thus in period  $t$  storsers chose  $q_{jt+1}$  to maximize

$$E_t\{u_{t+1}^S(q_{jt+1}, \mathbf{q}_{-jt+1}^*(\mathbf{p}_{-jt+1}^{ef}, q_{jt+1})) - q_{jt+1}p_{jt} - \mathbf{q}_{-jt+1}^*(\mathbf{p}_{-jt+1}^{ef}, q_{jt+1})' \mathbf{p}_{-jt+1}\}$$

where expectation is taken with respect to the distribution of  $-j$  prices.  $\mathbf{q}_{-jt+1}^*(\mathbf{p}_{-jt+1}^{ef}, q_{jt+1})$  represents optimal  $-j$  consumption in  $t + 1$  given price realizations and pre-stored quantities. Basically, at  $t$  the consumer chooses product  $j$  purchases knowing  $-j$  consumption is contingent on the eventual  $-j$  price.

With a general price support the problem is solvable but it can be tedious since it requires solving for  $\mathbf{q}^*$  for each point in the support of prices. The computation is much easier (especially for a small number of products) if we assume a two price support:  $p_j^N$  and  $p_j^S$ . For example, suppose Coke is on sale and Pepsi is not, the consumer has to decide how much Coke to purchase for  $t + 1$  knowing Pepsi's price at  $t + 1$  may end up at one of two different levels. The demand for Coke involves the solution of three first order conditions for:  $q^C$ ,

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<sup>2</sup>The only minor subtlety is whether consumers that stockpiled buy additional units should the realized price be lower than the preceding price. It is possible that consumers purchase additional units given the low price, or that they pay no attention to products in categories for which they already stored (they do not even go through that aisle). Equation (5), as written, assumes the latter, but both options can be handled.



Coke purchase at  $t$  for consumption at  $t + 1$ ,  $\bar{q}^P$ , Pepsi consumption at  $t + 1$  if Pepsi ends up being on sale, and  $\underline{q}^P$ , Pepsi consumption absent a sale.

While the two price support may come handy in the estimation of the rational expectations model, as we now explain, the model can still be estimated with an unrestricted price distribution. Notice that only in some states predicted behavior requires knowledge of future prices. For example, if both products are in  $SS$  demand does not depend on future prices.

In those states where predicted demand does not depend on future prices the predicted behavior as explained in the previous section is still valid, and can be used in the estimation under rational expectations. It turns out that in the 2 goods case, 10 of the 16 states (composed of the cross product of the 4 states of each good) predicted purchases of each product are the same under both expectations assumptions. In total only 2 out of the 16 states involve behavior that differs for both products. Thus, a way to estimate the model under rational expectation, without incurring additional computation costs and without the two price assumption, is to restrict the sample to periods where demand under both expectations assumptions coincide. We elaborate on this below.

## 2.3 Seller Behavior

We start by considering a monopolist facing a population of non-storers and storers with static demands given by  $Q^{NS}(p)$  and  $Q^S(p)$ . We drop the time subscript, but it is immediate to allow for changing demand. Marginal cost is  $c$ . Let  $p_S^*$  and  $p_{NS}^*$  be the prices that maximize –static– profits from separately selling to the populations of storers and non-storers, and  $p_{ND}^*$  the monopoly price of a non-discriminating monopolist facing the whole population, composed of non-storers and storers.  $p_{ND}^*$  maximizes  $(Q^{NS}(p) + Q^S(p))(p - c)$ . Denote  $\pi_{ND}^* = (Q^{NS}(p_{ND}^*) + Q^S(p_{ND}^*))(p_{ND}^* - c)$

### 2.3.1 Two-period problem

We initially consider optimal prices in a two period set-up. Storability may enable price discrimination if the seller would like to target storers with a lower price. Once storers purchase for future consumption the seller can target non-storers with higher prices.

In some cases a constant price might be optimal. It is, for example, if  $p_{NS}^* \leq p_S^*$ . On the other hand, suppose the seller charges  $\underline{p}$  in the first period and  $p_{NS}^*$  in the second period, for some  $p_S^* < \underline{p} < p_{NS}^*$ . Denote profits from  $\{\underline{p}, p_{NS}^*\}$  as:

$$\pi_{IPD}(\underline{p}) = (Q^{NS}(\underline{p}) + 2Q^S(\underline{p}))(\underline{p} - c) + Q^{NS}(p_{NS}^*)(p_{NS}^* - c)$$

The first term represents variable profits during sales, targeting storers who purchase for two periods, and non-storers for one period. The last term represents profits from non-storers, during non-sale periods. If

$$\pi_{IPD}(\underline{p}) > 2\pi_{ND}^* \quad (9)$$

for some  $p_S^* < \underline{p} < p_{NS}^*$  then the pair  $\{\underline{p}, p_{NS}^*\}$  does better than constant prices. Since the best constant price is  $p_{ND}^*$ , the above inequality guarantees all other constant prices do worse than the proposed price pair. It is an empirical matter whether constant or increasing prices are profitable. It depends on whether – using Robinson (1933)’s terminology – non-storers are the strong market while storers the weak market.

We assume throughout the concavity of objective functions. Thus assuming condition (9) holds then an increasing price sequence is optimal and the prices  $\underline{p}$  and  $p_{NS}^*$  are determined by the solution to the following first order conditions:

$$\begin{aligned} p_{NS}^* &= c - \frac{Q^{NS}(p_{NS}^*)}{\left. \frac{\partial Q^{NS}(p)}{\partial p} \right|_{p=p_{NS}^*}} \\ \underline{p} &= c - \frac{Q^{NS}(\underline{p}) + 2Q^S(\underline{p})}{\left. \frac{\partial(Q^{NS}(p) + 2Q^S(p))}{\partial p} \right|_{p=\underline{p}}} \end{aligned} \quad (10)$$

### 2.3.2 Multiple-period problem

In a longer horizon we need to show that the price sequence proposed in the previous section is feasible, and that no other price sequence does better. Consider horizons of length  $R > 2$ . It is immediate to see that for any  $R \leq T + 1$  the analysis of the previous section is still valid, with optimal prices being  $\underline{p}$  for one period -to supply storers- followed by  $p_{NS}^*$  afterwards. As long as the horizon is no longer than the storing period the seller clears storers out of the market and then targets non-storers.

In longer horizons,  $R > T + 1$  –if discrimination is profitable- cyclical prices are optimal. The simplest case to consider is  $T = 1$ ; the analysis is similar for larger  $T$ . We still assume the monopolist can commit to future prices; we later argue that the same predictions arise absent commitment, and under duopoly with commitment.

The monopolist maximizes profits

$$\sum_{t=1}^R \pi(p_t | p_{t-1}) = \sum_{t=1}^R X_{jt}(p_t, p_{t-1}, p_{t+1})(p_t - c)$$

where  $X_{jt}(p_t, p_{t-1}, p_{t+1})$  is given by 5. As before, we assume a finite horizon to avoid an infinite sum due to the lack of discounting. The maximization boils down to picking a sequence of prices, such that if  $p_{t-1} \leq p_t$  storers stockpile for future use.

**Proposition 1** *Under condition (9) optimal pricing involves cycles of  $\underline{p}$  followed by  $\bar{p}$ , with  $p_S^* < \underline{p} < \bar{p} = p_{NS}^*$*

**Proof.** First consider the last two periods in isolation. Under condition 9 optimal prices are  $\underline{p}$  followed by  $\bar{p}$ .

Now look at a 4-period problem. The proposed cycle is feasible and attains twice the profits of the two period problem. To see it is feasible notice that the candidate prices do not generate storage between periods 2 and 3. Absent a link between period 2 and 3, consumers behave as prescribed in each independent cycle (the first cycle is periods 1 and 2, the second is periods 3 and 4).

It remains to be shown that no other price sequence is more profitable. First notice that for any price sequence with  $p_2 > p_3$  to be optimal it has to be our candidate  $[\underline{p}, \bar{p}, \underline{p}, \bar{p}]$ . Since  $p_2 > p_3$  implies no storage in period 2, thus the two cycles are detached. The solution to the detached problems involves  $\underline{p}$  followed by  $\bar{p}$  in each part.

It remains to rule out price sequences that involve storing in period 2, i.e., sequences with  $p_2 \leq p_3$ . If  $p_2 \leq p_3$  consumers store in period 2. Having purchased for period three consumption in period two, in period three storers would only purchase for period four consumption, and they would do so only if  $p_3 \leq p_4$ . Suppose that indeed storers purchase in period three for period four consumption. Since storers are absent in period four, the optimal  $p_4$  is  $\bar{p}$  while the best third period price is  $p_{ND}^*$ . In the alternative case, in which storers do not purchase in period three the optimal price on period three is  $\bar{p}$  followed by  $p_{ND}^*$  in period four, since in the last period all customers are present (and there are no further purchases for storage). Lets go back to the first two periods. There are two cases to consider, either storers store in period one or they do not. If they store the only candidate for first period price is  $\underline{p}$ , moreover, in period two they store for period three, thus the optimal price is  $p_{ND}^*$ . If they do not store in period one the optimal first period price is  $p_{ND}^*$ , while the second period optimal price is  $\underline{p}$ . Thus, the optimal prices in the first two periods (given storage between periods two and three) are:  $\{p_{ND}^*, \underline{p}\}$  or  $\{\underline{p}, p_{ND}^*\}$  followed by  $\{\bar{p}, p_{ND}^*\}$  or  $\{p_{ND}^*, \bar{p}\}$  in periods three and four. Either way profits amount to  $2\pi_{ND}^* + \pi_{IPD}(\underline{p})$  which by condition 9 is lower than  $2\pi_{IPD}(\underline{p})$ . Thus, the cycling prices do better than any other price sequence in the four period problem.

It is interesting to notice that the cycle delivers discrimination twice, while the best alternative pricing that links periods achieves once the discriminating profit level and for two periods the non-discriminating profit level. Cycling prices maximize the times the seller discriminates across buyers.

We can keep adding two-periods at a time and apply the same reasoning. The cycle is feasible, and optimal assuming no storage between cycles. On the other hand, a sequence that induces storage between cycles, as above, fails to exploit discrimination at least once.

Finally, we need to consider odd  $R$ . It is easy to see that as we go from two to three periods the best the seller can get is  $\pi_{ND}^* + \pi_{IPD}(\underline{p})$ , namely, one event of discrimination plus a non-discriminating profit flow. The same is true for any  $R$ -long horizon. ■

The proposed sale cycle leads to a flow profit (per two-period cycle) of  $\pi_{IPD}(\underline{p})$ . The prediction is similar to Narasimhan and Jeuland (1985), which shows that cyclical pricing (sales) help sellers intertemporally price discriminate when buyers with more intense needs have more limited storage.

It is not difficult to show that the non-commitment solution coincides with the commitment solution. The proof is a little tedious as it involves many cases, but roughly consider what the possible deviation are. Lowering prices on a non-sale period is of no benefit, while raising during a sale period does not help either (since it eliminates a discrimination event).

### 2.3.3 Duopoly

In the context of our application there is more than one manufacturer. We show that in the commitment equilibrium both sellers charge cycling prices.

Consider firm  $j$  taking as given firm  $i$ 's cycling prices. Since storers always purchase good  $i$  at the sale price, their demand is  $Q_j^S(p_j, \underline{p}_i)$ , namely, it is the same in every period regardless of the current price of product  $i$ . In contrast, the non-storer's demand  $Q_j^{NS}(p_j, p_i)$  depends on the contemporaneous price of product  $i$ .

Define non-discriminating profits by firm  $j$  for each of the two prices charged by  $i$  as:  $\pi_{ND}^*(p_i)$ . We can now modify 9 for the duopoly case. The following is a sufficient condition for discrimination to be profitable in a two-period set up:

$$(Q_j^{NS}(\underline{p}_j, \underline{p}_i) + 2Q_j^S(\underline{p}_j, \underline{p}_i))(\underline{p}_j - c) + Q_j^{NS}(\bar{p}_j, \bar{p}_i)(\bar{p}_j - c) > \pi_{jND}^*(\underline{p}_i) + \pi_{jND}^*(\bar{p}_i) \quad (11)$$

Condition (11) says that in a two-period problem firm  $j$ , taking as given  $i$ 's low-high price sequence, gains from intertemporal price discrimination. Namely,  $j$  best responds using cycling prices.

The same reasoning used to show that cycles are optimal for the monopolist in a longer horizon, applies to the duopolist problem as well.<sup>3</sup>

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<sup>3</sup>There is an additional issue, the timing of the sales. It is possible that non-coincidental cycles are more profitable than coincidental sales. The issue does not arise in a two-period set up since there is no point of having a sale in the second period. We abstract for the moment from the timing issue, that could arise in a longer horizon, a condition like 11 would determine optimal timing.

## 3 Data and Estimation

### 3.1 Data

The data set we use was collected by Nielsen and it includes store-level weekly observations of prices and quantity sold at 729 stores that belong to 8 different chains throughout the Northeast US, for the 52 weeks of 2004. We focus on 2-liter bottles of Coke, Pepsi and store brands, which have a combined market share of over 95 percent of the market.

There is substantial variation in prices over time and across chains. A full set of week dummy variables explains approximately 20 percent of the variation in the price in either Coke or Pepsi, while a full set of chain dummy variables explains less than 12 percent of the variation.<sup>4</sup> On the other hand, a set of chain-week dummy variables explains roughly 80 percent of the variation in price. Suggesting similarity in pricing across stores of the same chain (in a given week), but prices across chains are different. It seems that all chains charge a single price each week. However, three of the chains appear to define the week differently than Nielsen. This results in a change in price mid week, which implies that in many weeks we do not observe the actual price charged just a quantity weighted average. In principle we could try to impute the missing prices. Since this is orthogonal to our main point we drop these chains.

Figure 2 displays the distribution of the price of Coke in the five chains we examine below. For some of the results below we need to define a sale price – a price in which consumers stockpile. The distribution seems to have a break at a price of one dollar, so we define any price below a dollar as a sale, namely, a price at which storers purchase for future consumption. This is an arbitrary definition. A more flexible definition may allow for chain specific thresholds, or perhaps moving thresholds over time. For the moment we prefer to err on the side of simplicity. Using this definition we find that approximately 30 (36) percent of the observations are defined as a sale for Coke (Pepsi). Interestingly, sales are somewhat asynchronized with only 7 percent of the observations exhibiting both Pepsi and Coke on sale (compared to a 10.5 percent predicted if the sales were independent).

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<sup>4</sup>These statistics are based on the whole sample, while the numbers in Table 2 below are based on only five chains as we explain next.

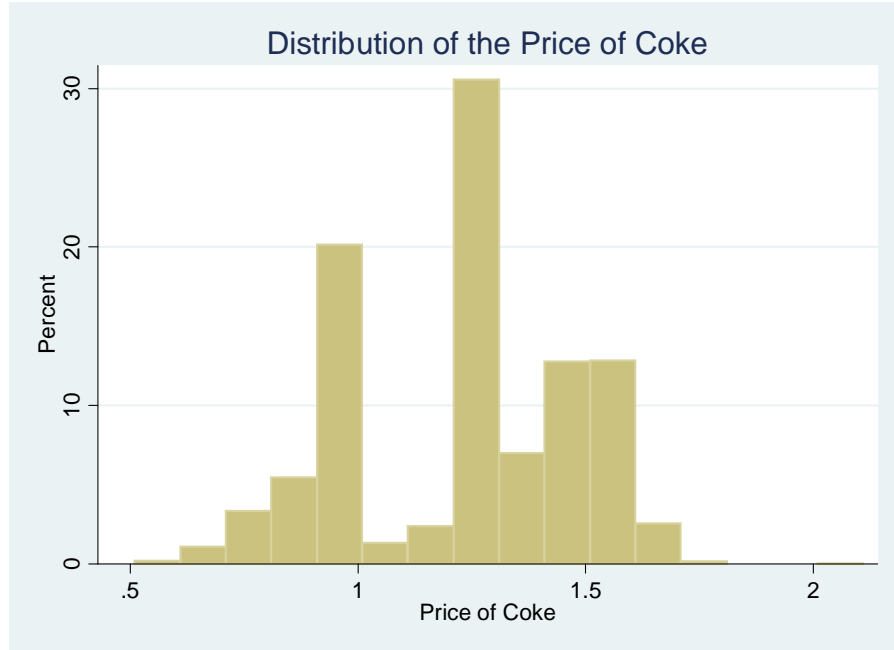


Figure 2: The Distribution of the Price of Coke

Note: The figure presents a histogram of the distribution of the price of Coke over 52 weeks in 729 stores in our data.

For the analysis below we use 24,674 observations from five chains. The descriptive statistics for the key variables are presented in Table 2.

Table 2: Descriptive Statistics

Variable	Mean	Std	% of variance explained by:		
			chain	week	chain-week
$Q_{Coke}$	446.2	553.2	5.6	20.4	52.5
$Q_{Pepsi}$	446.0	597.8	2.8	24.4	46.7
$P_{Coke}$	1.25	0.25	7.1	29.7	79.9
$P_{Pepsi}$	1.19	0.23	7.5	30.7	79.8
Coke Sale	0.30	0.46	6.4	30.0	86.6
Pepsi Sale	0.36	0.48	9.3	29.2	89.0

Note: Based on 24,674 observations for five chains, as explained in the text. As sale is defined as any price below one dollar.

## 3.2 Identification and Estimation

We estimate the parameters of the model by matching observed purchases and those predicted by the model. The estimation follows standard methods where the exact form of demand varies by (observable) state. It is simplest to see in the case of  $T = 1$ . As we can see in equation (8) the predicted purchase at time  $t$  has three terms: the demand by non-storers, demand by storers for  $t$  and demand by storers for  $t + 1$ . Each of these terms has the functional form of the static demand function given in (4). Depending on the state one or both of the demand terms for the storers might be zero. The same idea holds for higher  $T$  (in general there are  $T + 2$  terms). The prices that enter the demand terms are effective prices, defined in equation (6), which impacts estimates of cross price effects. Notice that effective prices are functions of actual prices and not averages within a state.

The parameters of the model are identified from market level data by conditioning on past and future prices holding current prices constant. For example, under A3 and  $T = 1$ , periods when  $p_{t-1} < p_t$  and  $p_t > p_{t+1}$  identify the preferences of non-storers, since storers do not purchase in these periods. The preferences of storers are identified, for instance, from periods when  $p_{t-1} \geq p_t > p_{t+1}$  and periods when  $p_{t-1} \leq p_t < p_{t+1}$ . In both these periods storers buy for a single period so after netting out the demand of non-storers from the total amount purchased the demand of storers can be identified.

We present estimates under perfect foresight and rational expectations. In the rational expectations model, with 2 products and  $T = 1$ , there are 16 states (4 for each product). In 10 of these states the purchasing pattern predicted by the rational expectations model equals the perfect foresight model, using the same definition of a sale, and therefore we can recover preferences under rational expectations by restricting the sample to those states. For example, suppose the Coke state is  $NN$ . If the Pepsi state is either  $NN$  or  $NS$  then both models predict purchases for consumption today using the current price of Pepsi as the relevant cross price. However, if the Pepsi state is either  $SS$  or  $SN$  then the models differ in their prediction. Under both models the consumer bought Pepsi at  $t - 1$  for consumption at  $t$ , but the models differ in how much was bought and therefore how much Coke is bought at  $t$ .<sup>5</sup>

For estimation we assume demand for product  $j$  at store  $s$  in week  $t$  is log-linear:

$$\log q_{jst}^h = \omega^h \alpha_{sj} - \beta_j^h p_{jst} + \gamma_{ji}^h p_{ist} + \varepsilon_{jst}, \quad j = 1, 2 \quad i = 3 - j \quad h = S, NS \quad (12)$$

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<sup>5</sup>In addition to the example in the text, the other 4 states where the models differ in their prediction for Coke purchases are when the Coke state is  $NS$  and Pepsi state is either  $NN$  or  $SN$ , or Coke state is  $SS$  and Pepsi state is either  $NN$  or  $SN$ . Symmetric arguments hold for Pepsi.

where  $\alpha_{sj}$  is a store specific intercept for each brand, and  $\varepsilon_{jt}$  is an i.i.d. shock. The parameters  $\omega^h$  allow for different intercepts for each consumer type. We scale these parameters to add up to one and define  $\omega = \omega^{NS} = 1 - \omega^S$ , as the relative intercepts which is also the fraction of non-storers when all prices are zero.

We also experimented with a linear demand specification. In general, the demand results, such as the difference between the static and dynamic model and the differences between storers and non-storer, are similar. However, in the linear model predicted demand can be negative (specially storers' demand at a high price). The log-linear specification avoids the negativity problem by imposing an asymptote to zero consumption as price increases.

We estimate all the parameters by non-linear least squares. We minimize the sum of squares of the difference between the observed purchases and purchases predicted by the model. We present the exact estimating equations in the Appendix. We should stress that in all cases we use actual prices: the definition of sales is used to define the states but in no way do we modify or average prices within state. In principle, we could use instrumental variables to allow for correlation between prices and the econometric error term. However, we do not think correlation between prices and the error term is a major concern in the example below. To obtain the exact estimating equations we combine equations (5) and (12), and allow for store fixed effects. To account for the store level fixed effects we demean the data, which makes all the parameters enter the equations non-linearly. Still the estimation is quite straightforward. We show in the Appendix how to modify the estimating equation to account for the fixed effects.

## 4 Results

### 4.1 Demand Estimates

The estimation results are presented in Tables 3 and 4. The different columns present estimates under alternative assumptions. In all cases the dependent variable is the (log of the) number of 2-liter bottles of Coke or Pepsi sold in a week in a particular store. All regressions include store fixed effects as well as the price of the store brand.

#### 4.1.1 Main Results

The first two columns in Table 3 display estimates from a static model. The rest of the columns present estimates from the dynamic model under different assumptions. In all cases we assume  $T = 1$  and allow for different price sensitivity for storers and non-storers. We also impose two restrictions. First, we impose the same  $\omega$  for Coke and Pepsi. We could allow for two parameters, but consistent with the idea of a population of storers who decide what



product to purchase we impose the same parameter. Second, the cross price effect between Coke and Pepsi is imposed to be symmetric.

Columns 3 and 4 present estimates from the model with perfect foresight (assumption A3) and defining sales based on actual prices: consumers stockpile if prices at  $t$  are lower than  $t + 1$  prices. The next set of columns continue to assume perfect foresight but uses a different definition of a sale. Now a sale is defined as any price below 1 dollar: whenever a buyer observes a price below a dollar they purchase for future consumption.<sup>6</sup> In both cases, the definition of a sale is just used to define the state. We do not average prices within a state: actual prices are used.

The final set of columns continue to define a sale as any price below 1 dollar but assume rational expectations instead of perfect foresight. As we discussed in Section 2.2.4, the rational expectations model requires us to solve a system of equations. Alternatively, we can estimate the model by restricting the sample to periods in which predicted demand does not depend on future prices. This is the approach we follow in the last columns. Hence the perfect foresight and rational expectations models deliver the same predictions and therefore the only difference with the estimation in columns 5 and 6 is in the periods used. Indeed, because of the conditioning, to such states, the number of observations goes down from 45,434 to 30,725.<sup>7</sup>

Overall, the results from all three models are similar. For the purpose of computing the benefits from price discrimination the key is the heterogeneity in the price sensitivity. The three models suggest almost identical numbers: non-storers are significantly less price sensitive than storers. This is consistent with price discrimination being a motivation for the existence of sales. The main difference across the three sets of results is in the cross-price elasticity of storers. The lower cross price effects under perfect foresight perhaps suggests A3 introduces measurement error. For of the calculations below the difference between the models is not of great importance.

The parameter  $\omega$  measures the relative intercepts of the demand for the two consumer types. This is not a measure of the relative importance of the two groups. Since storers are more price sensitive they will be a smaller fraction of demand at actual prices. Indeed, as we will see below for most observed prices demand from non-storers will constitute the majority of quantity sold.

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<sup>6</sup>Predictions differ, for example, when  $p_t = 0.99$  and  $p_{t+1} = 0.95$ . In the second model, at  $t$  consumers purchase for future consumption while in the former they wait for the better price at  $t + 1$ .

<sup>7</sup>The main reason to present the model in columns 5 and 6 is to separately show the effect of the change in the definition of a sale from the effect of the change in the sample.

Table 3: Estimates of the Demand Function

	Static Model		Dynamic Models					
	Coke	Pepsi	PF		PF-Alt Sale Def		RE	
			Coke	Pepsi	Coke	Pepsi	Coke	Pepsi
$P_{own}$ non-storers	-2.30 (0.01)	-2.91 (0.01)	-1.41 (0.02)	-2.11 (0.02)	-1.49 (0.02)	-2.12 (0.02)	-1.27 (0.02)	-1.98 (0.03)
$P_{cross}$ non-storers	0.49 (0.01)	0.72 (0.01)	0.61 (0.01)		0.71 (0.01)		0.63 (0.01)	
$P_{own}$ storers			-4.37 (0.06)	-5.27 (0.06)	-4.38 (0.07)	-5.08 (0.07)	-5.57 (0.12)	-6.43 (0.12)
$P_{cross}$ storers			0.61 (0.04)		0.34 (0.04)		2.12 (0.09)	
$\omega$	–	–	0.14 (0.01)		0.10 (0.01)		0.21 (0.02)	
# of observations			45434		45434		30725	

Note: All estimates are from least squares regressions. The dependent variable is the (log of) quantity of Coke sold at a store in a week. All columns include store fixed effects. Columns labeled PF use perfect foresight (Assumption A3), while columns labeled RE use rational expectations (Assumption A3'). Columns 3 and 4 define the states using actual prices, while the last four columns use the alternative definition of a sale as any price below 1 dollar. The RE model uses the alternative definition of sale but restricts the sample. See the text for details. Standard errors are reported in parentheses.

The own price elasticity implied by the dynamic results evaluated at the quantity weighted price for Coke is 2.16 and for Pepsi 2.78, while the elasticities implied by the static estimates are 2.46 and 2.94, respectively. As expected, neglecting dynamics in the estimation overstates own price elasticities.

#### 4.1.2 Sensitivity Analysis: Heterogeneous Storage

Until now we assumed  $T = 1$ . We now examine the sensitivity of the results to the definition of  $T$ . The first two sets of columns, in Table 4, present estimates of the same model as in columns 3-4 of Table 3, but assuming  $T = 2$  and  $T = 3$ , respectively. The results are very similar to those in Table 3. The main change is that the estimates compensate somewhat for the storers' extra periods of storage by: slightly increasing the fraction of non-storers and the price sensitivity of the storers.

Since the results are similar we want a way to select between the different values of  $T$ . The last two sets of columns do this. We allow for 3 types: non storers, consumers who

can store for  $T = 1$  (denote their fraction  $\omega_{T=1}$ ) and consumers who can store longer, either  $T = 2$  or  $T = 3$ . We look at the fraction of each type of consumers.

In columns 5-6 the fraction of non-storers is 0.15. Essentially identical to the estimates in Table 3. The fraction of consumers who can store for  $T = 1$  periods is 0.84, suggesting that roughly 1% of consumers store for  $T = 2$ . Thus, the  $T = 2$  type are non significant relative to the  $T = 1$  type.<sup>8</sup> The last pair of columns paint a similar picture. Here the fraction of consumers who store for 3 periods is less than 5%. These results suggest that  $T = 1$  is the preferred option.

Table 4: Estimates of the Demand Function

	PF-T=2		PF-T=3		PF-T=1,2		PF-T=1,3	
	Coke	Pepsi	Coke	Pepsi	Coke	Pepsi	Coke	Pepsi
$P_{own}$ non-storers	-1.62 (0.02)	-2.37 (0.02)	-1.97 (0.02)	-2.42 (0.02)	-1.44 (0.02)	-2.09 (0.02)	-1.43 (0.02)	-2.10 (0.02)
$P_{cross}$ non-storers	0.67 (0.01)		0.69 (0.01)		0.64 (0.01)		0.64 (0.01)	
$P_{own}$ storers	-4.25 (0.07)	-5.47 (0.09)	-5.31 (0.12)	-5.09 (0.11)	-4.34 (0.06)	-5.20 (0.06)	-4.31 (0.06)	-5.21 (0.07)
$P_{cross}$ storers	0.81 0.04		0.78 (0.09)		0.65 (0.04)		0.79 (0.04)	
$\omega$	0.31 (0.02)		0.41 (0.03)		0.15 (0.01)		0.17 (0.12)	
$\omega_{T=1}$					0.84 (0.02)		0.78 (0.02)	

Note: All estimates are from least squares regressions. The dependent variable is the (log of) quantity of Coke sold at a store in a week. All columns include store fixed effects. In all columns we estimate the model with perfect foresight, the differences are in the length of T and the number of different types of consumers. Standard errors are reported in pharenthesis.

## 4.2 Implications for Pricing and Welfare

We now examine the implications of the estimates. We focus on the role of sales as a form of intertemporal price discrimination and its welfare implications. We consider two benchmarks: (non-feasible) third degree discrimination, targeting storers and non-storers with different prices, and nondiscrimination, a single price for all consumers.

<sup>8</sup>Since the price sensitivity of all storers is the same the relative fraction of  $T = 1$  consumers and  $T = 2$  consumers will stay the same at all prices.

The analysis neglects the vertical relation between manufacturer and retailer, which could generate double marginalization. The relation between retailers and manufacturers is quite interesting and subtle, but beyond the scope of this paper. The first order conditions in equation (10) represent either a manufacturer selling to a competitive retailing industry or integrated pricing with transfers (which avoids double marginalization).

#### 4.2.1 Markups and Profits

A standard exercise is to use demand estimates and a first order condition from a static profit maximization to infer markups and marginal costs. Following this approach and using the first two columns of Table 3 we get an implied markup for Coke of 43 cents, and 34 cents for Pepsi. Subtracted from a quantity weighted average transaction price of 1.07 and 1.01, respectively, leads to marginal costs of 66 and 67 cents respectively.

Repeating this calculation using the dynamic demand estimates reported in Table 3, but still relying on a static first order condition, the implied margin for Coke is 50 cents and a marginal costs of 57, while 37 and 64 cents for Pepsi. The lower dynamic elasticities translate into higher implied mark-ups.

Naturally, demand dynamics render the static first order conditions inadequate as a description of seller behavior. So we now turn to the dynamic pricing model. We compute prices and profits under non-discrimination, third degree discrimination and sales. We assume the marginal cost during sale and non-sale periods is the same. Since each first order condition delivers a different marginal cost, we use the average across the regimes to compute prices and profits.

Table 5 displays the optimal regular, non-sale, prices and sale prices for Coke and Pepsi under the different pricing assumptions. We also show profits relative to discrimination. By discrimination we mean the case where the firms can identify the storers and non-storers, set different prices for each group and prevent arbitrage. This is of course non-feasible but serves as a benchmark to measure the maximum attainable gains from third degree price discrimination.

By comparing the discriminatory and non-discriminatory prices we see the potential role of sales in targeting price sensitive buyers with a lower price. The optimal non-discriminatory price is 1.11 for Coke and 1.04 for Pepsi. These prices are in between the discriminatory prices for both products: 1.31 and 0.83 for Coke and 1.14 and 0.86 for Pepsi. Non-storers, being less price sensitive, are targeted with higher prices than storers. The discriminating prices target non-storers with 58% higher Coke prices than storers' prices. The gap is 33% for Pepsi.

Rows labeled 3 and 4 present prices and profits under two different models of sales. The numbers in row 3 use the demand estimates from columns 3-4 of Table 3 ( $T = 1$  and perfect

foresight) and in row 4 we present, for robustness, the results for the  $T = 2$  model with perfect foresight (columns 1-2 in Table 4). In all cases we assume the competitor charges the non-discriminatory price. The exercise amounts to evaluating the impact of different pricing taking as given competitor's behavior. In the next section we evaluate equilibrium regimes where both players discriminate.

The optimal sale price is in between the non-discriminatory price and the storers' discriminating price. It differs from the non-discriminatory price because it targets a population with a higher proportion of storers, since they purchase for two periods. By placing more weight on the price sensitive buyers, the sale price is lower than the non-discriminating one. The estimates imply for Coke a sale price about 8% below the non-discriminatory price, and 5% lower for Pepsi.

The column labeled profit, displays the fraction of the discriminating profits (the highest the seller can get) accrued without discrimination and through sales, respectively. For example, for Coke the non-discriminatory seller gets 88% of the discriminating profits, while sales accrue between 91% of the discrimination benchmark.

Table 5: Gains from sales

#	Pricing	Coke			Pepsi		
		Regular(\$)	Sale(\$)	Profit(%)	Regular(\$)	Sale(\$)	Profit (%)
1	Non-discrimination	1.11	–	88	1.04		92
2	Discrimination			100			100
	non-storers	1.31			1.14		
	storers	0.83			0.86		
Sales							
3	T=1	1.31	1.02	91	1.14	0.99	94
4	T=2	1.27	0.95	95	1.14	0.95	97

Note: Computed based on the estimates of columns 3-4 of Table 3, and columns 1-2 of Table 4 (for the T=2 case.) The columns labeled Regular and Sale present the regular and sale price, respectively. The column labeled Profit is the percent profit in each regime relative to profits under discrimination. The marginal cost used in each case is computed using first order conditions averaged across different states. The imputed mc are 0.6 for Coke and 0.67 for Pepsi.

In row 4 we examine the impact of a longer storage horizon,  $T = 2$ . In this model sales are deeper, as they are aimed at demand that places more weight on storers who purchase for current consumption and two periods ahead (and not just one period ahead as in the  $T = 1$  model). In turn, sales more effectively capture additional gains from discrimination, 95% and 97% of the target for Coke and Pepsi respectively. Thus, capturing around 50% of the gap in profits between discrimination and non-discrimination.

### 4.2.2 Welfare

The welfare consequences of third degree price discrimination had been studied since Robinson (1933). The standard intuition is that in a monopoly situation price discrimination will yield lower prices in the weak market, where the demand is more price sensitive, and higher prices in the strong market, relative to the non-discriminatory price.<sup>9</sup> So while sellers are better off, some consumers are better off and others worse off. The overall impact of discrimination is an open question subsequently studied by Schmalensee (1981), Varian (1984), Aguirre, Cowan and Vickers (2010) among others. A necessary condition for welfare to improve is that quantity sold increases. Since the allocation of goods across markets is distorted, a constant –or lower– output would necessarily lead to lower total surplus (for a formal proof see Schmalensee (1981)).

In the context of a duopoly the picture is slightly more complex, as it is not even clear sellers are better off under discrimination. Few papers provide theoretical results. Borenstein (1985) and Holmes (1989) offer conditions for output to increase under duopoly, and simulations showing profits may decline. Corts (1998) shows that even with well behaved profit functions all prices can decrease when the weak market of one firm is the strong market of the other.

In this section we evaluate the impact of intertemporal discrimination on quantity and welfare. We first consider the implication of our estimates for a monopolist (i.e., a duopolist that unilaterally best responds to given competitor behavior), and compare the findings to the theoretical literature. We then consider the duopoly case where there is little theoretical guidance.

**Best Responses** As a first step we compute quantity changes holding fixed the behavior of competitors and assuming these competitors do not price discriminate. This allows us to isolate the impact of different pricing strategies. An additional advantage of this exercise is that it is linked to the theoretical results in Schmalensee (1981) and Aguirre et. al. (2010), since the seller is basically a monopolist.

It is worth mentioning that the third-degree discrimination theoretical results apply to the intertemporal price discrimination as well. We just need to reinterpret demand during sale periods,  $Q^{NS}(p) + 2Q^S(p)$ , as the weak demand, and demand during non-sale periods,  $Q^{NS}(p)$ , as the strong demand.

Before looking at the numbers in Table 6 we turn to the theoretical literature for predictions and to make sure the functional forms we use are not responsible for our findings.

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<sup>9</sup>The direction of price changes indeed follows this pattern if the monopolist's profit function is strictly concave in price within each segment. When this is not the case the direction of price changes is ambiguous (see Nahata, et al. (1990))

Proposition 3 in Aguirre et al. (2010) encompasses our demand framework. They show that welfare depends on the relative concavity of the demand functions in the two markets. Our estimates deliver a more convex demand in the weak market, which is one of the conditions singled out in Robinson (1933) for quantity to increase under discrimination. In addition, what Aguirre et al. call the IRC condition<sup>10</sup> holds for exponential demands, thus Proposition 3 therein applies. Proposition 3 is a comparative static with respect to the degree of price discrimination.<sup>11</sup> Proposition 3 shows that, for our estimated demand, welfare increases in the extent of discrimination and then declines. A little discrimination is welfare improving, full discrimination could deliver higher or lower welfare. In sum, even in the monopoly case the impact on welfare is indeterminate. It is an empirical matter that we will evaluate with the estimates.

Table 6 shows prices, quantities, and profits under different pricing regimes for the different segments of the market. Quantities and profits are per week. Overall the table paints a clear picture. Both quantities and profits are higher under discrimination than non-discrimination. Intertemporal discrimination is in between. While intertemporal discrimination recovers about a quarter of the potential profit difference between discrimination and no discrimination, it delivers about half of the quantity increase.

It is interesting to see the breakdown by the consumer segments. It seems like sales are a fairly efficient way of recovering the potential profits from the consumers who store. Sales seem to recover over 50% of the potential profits from this group for Coke. The overall gains in profits is smaller because sales decrease profits slightly from the non-storing group. The same is true for the increase in quantity: it mostly comes from the storers. The non-storers end up paying almost an identical, slightly higher, quantity weighted price relative to non-discrimination.

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<sup>10</sup>The condition requires the ratio of the derivative of welfare with respect to price to the second derivative of profits be monotonic in price, in each market.

<sup>11</sup>They follow the analysis in Schmalensee and Holmes whereby the implications of discrimination are assessed by studying the behavior of a seller who is constrained to set prices in the weak and strong market no more than  $r$  units apart. As  $r$  increases the optimum approaches full discrimination.

Table 6: Quantity Effects (no PD by competitors)

	Coke			Pepsi		
	Price	Quantity	Profit	Price	Quantity	Profits
Non-Discrimination		318.00	161.86		425.27	157.45
non-storers	1.11	258.42	131.54	1.04	345.84	127.96
storers	1.11	59.58	30.32	1.04	79.43	29.39
3rd Degree Discrimination		397.44	184.58		482.79	170.60
non-storers	1.31	194.92	138.20	1.14	277.70	131.63
storers	0.83	202.52	46.38	0.86	205.09	38.97
Intertemporal Discrimination		353.12	167.78		446.06	160.44
non-storers-non-sale	1.31	194.92	138.20	1.14	277.70	131.63
non-storers-sale	0.99	307.36	118.64	0.98	394.18	121.41
storers - non-sale	1.31	0	0	1.14	0	0
storers - sale	0.99	101.98	39.36	0.98	110.12	33.92

Note: Computed based on the estimates of columns 3-4 of Table 3. Each entry shows the price/quantity and profits from each group under each regime.

**Equilibrium** We evaluate profits and consumer surplus, when all competitors adhere to each regime. In other words, instead of best responses, as we evaluated in the previous section, we compare a regime that allows for discrimination to another regime where discrimination is not allowed. The idea is to capture market performance under different rules (e.g., if discrimination was not allowed or feasible).

The first step is to check quantity increases, absent them, welfare is bound to decline. As Tables 7 and 8 show, for both products quantity increases under either form of discrimination, third degree and intertemporal. Notice that relative to Table 6, that evaluated unilateral discrimination –competitors pricing was taken as given– quantity changes are more modest. All increases are lower, and the decline in the strong market is smaller as well. Quantity effects are attenuated by the prices of the competitor who also discriminates.

The impact on profits is similar, aside from the strong market where interaction increases profits, overall profit gains are attenuated by the competitor also discriminating.

As expected, buyers in the strong market are worse off, while those in the weak market are better off. The column labeled  $\Delta CS$  displays the change in consumer surplus, measured by the equivalence variation<sup>12</sup>, relative to the non-discrimination case. In the case of third

<sup>12</sup>The equivalence variation (in this case identical to the compensating variation due to quasilinearity) of a change in two prices is the sum of the area under each demand curve as the respective prices change. That is, the area under the Coke demand curve fixing the initial Pepsi price, plus the area under the Pepsi curve fixing the final Coke price.



degree discrimination non-storers are worse off but storers are better off because they are offered lower prices. In the case of intertemporal discrimination, non-storers can partly benefit from the sales but are charged higher prices during non-sale periods; overall they are worse off. Storers are better off in both cases, but less so under intertemporal discrimination because the prices they are charged are not as low as under third degree discrimination.

Total consumer welfare is down under third degree discrimination: the gains to the storers are out weighed by the losses of the non-storers. In the case of sales the results differ between the products. For Coke consumer welfare slightly increases, while for Pepsi it slightly decreases. In both cases the non-storers are worse off by roughly the same amount. The difference is in the gains to storers: they are larger in the case of Coke because sales are deeper relative to non-discrimination.

Total profits increase under both forms of discrimination. Under third degree discrimination profits from both segments increase, while under sales profits from non-storers decrease.

Total surplus is higher under discrimination of either sort, than under a single price. Looking at total surplus by segment, for both products it decreased in the non-storers segment.

Table 7: Equilibrium Welfare Effects – Coke

	Price	Quantity	Profit	$\Delta CS$	$\Delta Profits$	$\Delta TS$
Non-Discrimination		318.00	161.86			
non-storers	1.11	258.42	131.54	–	–	–
storers	1.11	59.58	30.32	–	–	–
3rd Degree Discrimination		389.15	188.82	-12.33	26.96	14.62
non-storers	1.31	207.69	147.26	-45.04	15.72	-29.32
storers	0.83	181.46	41.56	32.71	11.24	43.95
Intertemporal Discrimination		350.02	168.65	4.54	6.78	11.33
non-storers - non-sale	1.31	207.69	147.26	-45.04	15.67	-29.32
non-storers - sale	0.99	295.96	114.24	34.71	-17.3	17.41
storers - non sale	1.31	0	0	–	–	–
storers - sale	0.99	98.19	37.90	9.70	7.58	17.28

Note: Computed based on the estimates of column 3 in Table 3. Each entry shows the price/quantity and profits from each group under each regime. The last three columns present the change in consumer surplus, profits and total surplus relative to non-discrimination, respectively.

Table 8: Equilibrium Welfare Effects – Pepsi

	Price	Quantity	Profit	$\Delta$ CS	$\Delta$ Profits	$\Delta$ TS
Non-Discrimination		425.27	157.35			
non-storers	1.04	345.84	127.96	–	–	–
storers	1.04	79.43	29.39	–	–	–
3rd Degree Discrimination		486.62	181.56	-16.38	24.21	7.83
non-storers	1.14	313.73	148.71	-36.49	20.75	-15.74
storers	0.86	172.89	32.85	20.10	3.46	23.56
Intertemporal Discrimination		441.87	162.14	-2.22	4.79	2.57
non-storers - non-sale	1.14	313.73	148.71	-36.49	20.75	-15.74
non-storers - sale	0.98	365.68	112.63	21.25	-15.33	5.92
storers - non sale	1.14	0	0	–	–	–
storers - sale	0.98	102.16	31.47	5.40	2.08	7.48

Note: Computed based on the estimates of column 4 in Table 3. Each entry shows the price/quantity and profits from each group under each regime. The last three columns present the change in consumer surplus, profits and total surplus relative to non-discrimination, respectively.

## 5 Concluding Comments

We study the impact of price discrimination when consumers can anticipate demand and store for future consumption. To make the problem tractable we offer a simple model to account for demand dynamics due to consumer inventory behavior. We estimate the model using store level scanner data and find that consumers who store are more price sensitive. This suggests that intertemporal price discrimination can potentially increase profits, which we then quantify. We find that sales can recover 24-30% of the potential gains from (non-feasible) third degree price discrimination. The estimates also suggest that total welfare increases when sales are offered.

A key to making our model tractable is the simplicity, some might say over-simplicity, of the demand model. Its important to note that in order to take the general demand model in Section 2.1 to the data one needs to also make some strong (mostly untestable) assumptions regarding, for example, the functional form of inventory cost and consumer expectations on how prices evolve (see, for example, Erdem, Imai and Keane, 2003, or Hendel and Nevo, 2006b). It depends on the application whether it is more reasonable to make the assumptions of this paper or those of the previous literature. If one is willing to make the assumptions herein the analysis is significantly simpler and in many issues, like the supply side, becomes tractable.

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## 7 Appendix: Estimating Equations

We choose the parameters to minimize the sum of squares of the difference between observed purchases and those predicted by the model. Let  $x_{jst}$  denote the purchases of product  $j$  in store  $s$  at week  $t$ . By equations (5) and (7), modifying for simplicity of presentation the indicator functions in (7) to ignore ties in effective prices, the purchases predicted by the model are given by

$$x_{jst} = q_{jst}^{NS} + x_{jst}^S = Q_{jst}^{NS}(p_{jst}, \mathbf{P}_{-j,s,t}) + \sum_{\tau=0}^T Q_{jst+\tau}^S(p_{jst}, \mathbf{P}_{-j,s,t+\tau}^{ef}) \mathbf{1}[p_{jst} = \mathbf{P}_{j,s,t+\tau}^{ef}]$$

In the case of  $T = 1$  the predicted purchases consist of three components: the purchases by non-storers and the purchases by storers for consumption at  $t$  and at  $t + 1$ . Depending on the state, one or both of the components of demand by non-storers can be zero (see equation 8). We want to stress that in all cases we use the actual prices. The definition of sales is only used to classify the states: prices are never changed.

The data consists of a panel of quantities and prices in different stores. Different stores operate at different scales and therefore attract a different number of customers and sell different average amounts. We account for this with a store fixed effect. Since purchases are scaled differently in different states in order to account for store fixed effects we need to transform the predicted purchases as follows. Given the functional form in equation and assuming the fraction of non-storers is given by  $\omega$ , (12)

$$Q_{jst}^{NS}(p_{jst}, \mathbf{P}_{-j,s,t}) = \omega e^{\alpha_{sj}} e^{\{-\beta_j^{NS} p_{jst} + \gamma_{ji}^{NS} p_{ist}\}} e^{\varepsilon_{jst}}$$

$$Q_{jst+\tau}^S(p_{jst}, \mathbf{P}_{-j,s,t+\tau}^{ef}) = (1 - \omega) e^{\alpha_{sj}} e^{\{-\beta_j^S p_{jst} + \gamma_{ji}^S p_{ist+\tau}^{ef}\}} e^{\varepsilon_{jst+\tau}}$$

Denote by

$$Q_{jst}^{*NS} = \omega e^{\{-\beta_j^{NS} p_{jst} + \gamma_{ji}^{NS} p_{ist}\}} e^{\varepsilon_{jst}} \quad \text{and} \quad Q_{jst+\tau}^{*S} = (1 - \omega) e^{\{-\beta_j^S p_{jst} + \gamma_{ji}^S p_{ist+\tau}^{ef}\}} e^{\varepsilon_{jst+\tau}}$$

then

$$x_{jst} = e^{\alpha_{sj}} \left( Q_{jst}^{*NS} + \sum_{\tau=0}^T Q_{jst+\tau}^{*S} \right)$$

and

$$\log(x_{jst}) - \overline{\log(x_{jst})} = \log \left( Q_{jst}^{*NS} + \sum_{\tau=0}^T Q_{jst+\tau}^{*S}(p_{jst}, \mathbf{P}_{-j,s,t+\tau}^{ef}) \right) - \overline{\log \left( Q_{jst}^{*NS} + \sum_{\tau=0}^T Q_{jst+\tau}^{*S}(p_{jst}, \mathbf{P}_{-j,s,t+\tau}^{ef}) \right)}$$

where  $\overline{\log(x_{jst})}$  denotes the average over weeks within a store and product. This transformation is equivalent to the standard "within" transformation, except that

$$\overline{\log \left( Q_{jst}^{*NS} + \sum_{\tau=0}^T Q_{jst+\tau}^{*S}(p_{jst}, \mathbf{P}_{-j,s,t+\tau}^{ef}) \right)}$$

depends on the parameters of the model and cannot be done prior to estimation. In other words we cannot transform the model prior to estimation rather the estimation routine needs to compute the average for each value of the parameters.