ASYMMETRIC PRICE ADJUSTMENT AND CONSUMER SEARCH: AN EXAMINATION OF THE RETAIL GASOLINE MARKET

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Abstract

It has been documented that retail gasoline prices respond more quickly to increases in wholesale price than to decreases. However, there is very little theoretical or empirical evidence identifying the market characteristics responsible for this behavior. This paper presents a new theoretical model of asymmetric adjustment that empirically matches observed retail gasoline price behavior better than previously suggested explanations. I develop a "reference price" consumer search model that assumes consumers' expectations of prices are based on prices observed during previous purchases. The model predicts that consumers search less when prices are falling. This reduced search results in higher profit margins and a slower price response to cost changes than when margins are low and prices are increasing. Following these predictions, I estimate the response pattern of retail prices to a change in costs and examine patterns of price dispersion. Unlike previous empirical studies I focus on how profit margins (in addition to the direction of the cost change) affect the speed of price response. The results show that prices are less responsive to cost changes when profit margins are large. Consistent with reference price search behavior, I also show that station prices exhibit more dispersion during periods when margins are high.

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1 Introduction

A large empirical literature provides evidence that retail gasoline prices respond faster to cost increases than to cost decreases.[1] The Los Angeles retail gasoline price series displayed in Figure 1 clearly demonstrates such asymmetric adjustment to wholesale cost. Asymmetric price adjustment is not unique to the gasoline market. The phenomenon has been observed and studied in a variety of industries.[2] As Peltzman (2000, pg. 468) points out, the prevalence of asymmetric price adjustment suggests “a serious gap in a fundamental area of economic theory.” However, little previous research has attempted to explain or empirically identify which characteristics of the retail gasoline market (or other markets) may be responsible for asymmetric price adjustment.[3] Particular forms of collusion or consumer search behavior have been suggested as being roughly consistent with asymmetric response. However, more detailed empirical analysis shows that these explanations may not match observed retail gasoline price behavior. I discuss an additional explanation based on consumer search, and empirically show that the resulting predictions are consistent with observed pricing patterns.

Gasoline purchasing behavior is often associated with models of consumer search.[4] Largely this is because both anecdotal and empirical evidence (**?**, Barron et al. (2004), Hosken et al. (2008)) suggest that significant price dispersion occurs in most retail gasoline markets even after controlling for heterogeneities across sellers. In addition, gas prices tend to change more frequently than in other markets making it increasingly difficult for consumers to maintain accurate price information. While some consumers actively observe gas prices during everyday driving and

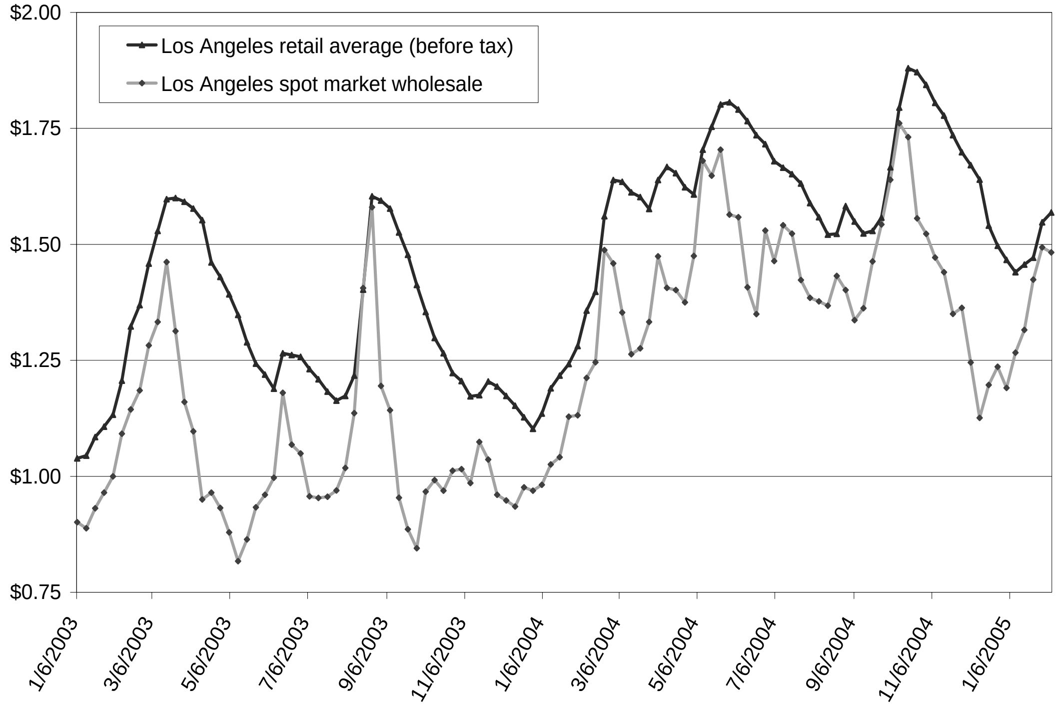
[1] Academic research addressing asymmetric adjustment of gasoline prices includes: Borenstein, Cameron and Gilbert (1997), Bacon (1991), Johnson (2002), Eckert (2002), Verlinda (2008), and Deltas (2008). Existing policy studies include: (GAO) U.S. General Accounting Office (1993), Department of Energy, Energy Information Administration (1999), and Finizza (2002).

[2] Peltzman (2000) examines prices in over 200 industries and finds evidence of asymmetric adjustment in a significant share of the sample. In addition, Goodwin and Holt (1999) and Goodwin and Harper (2000) estimate asymmetric adjustment in the U.S. beef and pork industries, and O’Brian (2006) estimates asymmetric adjustment in interest bearing deposit accounts.

[3] Johnson (2002) finds that diesel prices respond more quickly and less asymmetrically than gasoline prices to a change in costs. He suggests that this behavior may be consistent with a model of consumer search similar to the model developed in this paper. Eckert (2002) shows that Edgeworth Cycle equilibria can produce asymmetric adjustment and presents some empirical support using gasoline prices from Windsor, Ontario. However, the Edgeworth Cycle theory used by Eckert (2002) and Noel (2007) describes markets where retail prices frequently cycle up and down independently of wholesale cost. This price behavior is not observed in my sample or in the gasoline prices of most U.S. cities.

[4] See pioneering work by Marvel (1976).

Figure 1: Weekly Los Angeles Gasoline Prices 2003-2004.[a]



[a] These data are part of the longer time series of Los Angeles gasoline prices described in Section 4. Retail prices are Los Angeles average prices for 87 octane gasoline collected weekly, and wholesale prices are weekly averages of the Los Angeles spot market prices both reported by the U.S. Department of Energy.

may be fairly well informed about prices in their area, many consumers pay little or no attention to prices until they need to buy gas. Not only are consumers unlikely to know which station currently has the cheapest price, but they may also be unaware of changes that have occurred to the overall price level in the market due to wholesale price movements. For consumers with limited price information, their best guess about prices may be based on prices they observed earlier in the week or the last time they purchased.

In this paper I present a stylized model of consumer search where consumers form expectations about the price distribution based on a reference price.[5] In particular, I examine the case in which this reference price is the average price level from the previous period. While this

[5]This assumption differs from other search models, which almost always assume that consumers search as if the equilibrium price distribution is, in fact, known *a priori*.

assumption is rather strong, I suggest that it more accurately captures the behavior of typical gasoline consumers. Perhaps more importantly, the equilibrium search behavior that results from this assumption generates asymmetric price adjustment like that observed in retail gasoline markets, and is consistent with several other observed patterns of gasoline pricing behavior that can not be explained by other search models.

The asymmetric effect generated by the reference price search assumption is straightforward. If a cost increase puts upward pressure on prices, consumers expectations of the price distribution (based on last period's prices) will tend to be too low, causing them to search more than they otherwise would. More search leads to lower margins and less price dispersion. On the other hand, when costs and prices are falling, consumers will tend to search less generating higher margins and price dispersion. This asymmetric relationship between price changes and search intensity can create the type of asymmetric price response observed in the gasoline market. It also generates an interesting relationship between margins and the extent to which prices respond to cost changes. When costs become low relative to last period's prices (and, therefore, low relative to consumers' expectations of prices) firms only have the incentive to lower prices just enough to discourage consumers from searching.[6] As a result, when margins are high, cost fluctuations have little effect on equilibrium prices.

An empirical analysis of gasoline price dynamics explores some of the testable predictions of the reference price search model, and reveals several new and important properties of the response of retail prices to changes in cost. Much of the empirical analysis relies on estimating the expected retail price conditional on past values of price and wholesale cost. Using two different sources of gas station price data, I estimate an autoregressive model that allows for the nonlinear and asymmetric relationships predicted by the theoretical model. Consistent with other studies, the data suggest that retail prices respond more quickly to cost changes when costs are increasing than when they are decreasing. However, the empirical results suggest that margin size may be more important than the direction of the cost change in determining the speed of price response. By controlling for the size of current margins, I estimate that there is little difference in response

[6] Although margins are high in this situation, few consumers are searching and so firms are unable to attract more customers by undercutting rivals.

behavior to a positive and negative cost change.[7] In addition, there appears to be little variation across firms in response behavior, but price dispersion is shown to be higher during periods with high profit margins. These patterns advance the current understanding of how gasoline prices adjust to cost changes, and are consistent with the unique predictions of the reference price search model.

2 Reference Price Search Behavior

Stigler (1961) and others initiated the theory of consumer search as a rationalization of the price dispersion they observed in various markets. Nearly all of the models in the subsequent literature are based on the assumption that consumers search optimally given the equilibrium distribution of prices being charged.[8] The reference price search model relaxes this crucial assumption. In fact, the asymmetric price adjustment predicted in the model directly results from the assumption that consumers' expectations differ from the actual price distribution. I argue that incorporating imperfect knowledge of the general price level results in predicted pricing behavior that more closely matches that observed in retail gasoline markets.

Several other recent studies have constructed more traditional equilibrium search models that generate asymmetric price adjustment. In the spirit of Benabou and Gertner (1993), these models assume that consumers have fully rational expectations about prices conditional on firms having stochastic marginal costs drawn from a known distribution. Tappata (2009) and Yang and Ye (2008) develop dynamic versions of a basic equilibrium search model in which firms' costs evolve over time between a high and a low cost state according to a Markov process.[9] Consumers are assumed to know the process with which costs evolve, and either observe past cost draws (Tappata) or learn them from past price observations (Yang and Ye). In both models search responds asymmetrically to cost increases and decreases and this generates a form of asymmetric

[7] Overall, asymmetric adjustment still occurs since positive cost shocks tend to lead to low margins and fast response, and negative cost shocks lead to high margins and slow response.

[8] Surveys of this literature include McMillan and Rothschild (1994) and Baye et al. (2006). Several studies relax the assumption that consumers know the equilibrium price distribution *a priori*. These include Rothschild (1974), Benabou and Gertner (1993), and Rauh (1997).

[9] Cabral and Fishman (2008) develop a similar model, although the assumed cost structure is arguably less well suited to explain gasoline price fluctuations.

price adjustment. However, as I describe in Section 3, these models are unable to explain many of the specific patterns of price adjustment and consumer search observed in retail gasoline markets. This is because asymmetries in search behavior and price adjustment in the Tappata (2009) and Yang and Ye (2008) models are generated by a very different mechanism than in the model I present. In these models, when marginal costs increase this moves the lowest possible retail price closer to consumers' arbitrarily defined choke price causing equilibrium prices to become less disperse and consumers to search less. Such dependance on a binding choke price is a particularly uncomfortable property for retail gasoline markets, where demand is know to be highly inelastic in the short run.

The simple search model presented here is intended to illustrate more realistically how consumers' expectations affect search behavior and equilibrium prices. I start by identifying the equilibrium prices and level of consumer search in a particular period given the firms' marginal cost and consumers' current expectations about the price distribution. I show that if consumers' expectations are lower than the actual price distribution, consumers search more and prices are closer to marginal cost. On the other hand, if consumers' expectations are too high, they search less and average price margins are larger. I then assume that consumers expectations are based on the average price from the previous period, and examine how prices and search behavior respond to changes in marginal cost.

The behavioral effect of assuming that consumers' price expectations differ from the actual price distribution is seen most strongly in the initial decision of whether to purchase from the first seller one visits or to search for a better price. This is because the decision to purchase from the first seller is made purely by comparing that station's price to the expected price distribution. If consumers searched stations sequentially and updated their expectations after each observation, the effect of the prior on search behavior would diminish as the consumer continued to searched. In order to isolate the impact of consumers' priors on search behavior I abstract to a two firm model in which consumers simply decide to search or not.

2.1 Static Search Model

Consider a market with 2 identical firms producing a homogeneous good. Both firms have zero fixed costs and a marginal cost c.[10] There are N consumers who each have unit demand for the good (up to a very high price).[11] Consumers' expectations of prices are defined by a distribution with a continuous c.d.f. of $L(p)$ and p.d.f. of $l(p)$ (which are identical for all consumers). These expectations are assumed to be exogenously determined in the static game. When considering dynamic predictions and asymmetric price adjustment in the next section I assume that these expectations are formed from past price levels. However, in the static model I make no assumptions about how these expectations are determined, aside from the fact that they are not required to equal the actual equilibrium price distribution. Consumers are also assumed to have no information about firms' marginal cost.

Each consumer randomly observes the price at one of the firms. Then the consumer must choose between purchasing from that firm or paying a constant search cost k to observe the other firm's price. Consumers' search costs are randomly distributed across the population with a minimum of zero, a continuous c.d.f. of $G(k)$, and a p.d.f. of $g(k)$. I further assume the distribution of search costs, $G(k)$, has an increasing hazard rate, in order to ensure that the firms' profit functions have a unique maximum.[12] To account for the case in which some consumers are always informed, I allow for the possibility of a mass of consumers with zero search cost. Once a consumer chooses to search, he may purchase from either firm at no additional cost.[13]

Henceforth, the two firms are called Firm 1 and Firm 2, and the consumers who originally observed the price at Firm 1 are called Firm 1's consumers. The prices the firms charge are p_1 and p_2 respectively. Since the firms are identical and the consumers of each firm are identical, any result about Firm 1's behavior also holds for Firm 2. After observing p_1, Firm 1's consumers search

[10] Fixed (sunk) costs are irrelevant here since I am only studying the short run dynamics of competition between firms. They are assumed to be zero for notational simplicity.

[11] This assumption implies a nearly infinite monopoly price. However, unlike in other search models, consumers' search decisions are based on comparisons to their expectation of price rather than on actual price dispersion. These search patterns generate residual demand elasticity that makes the reservation price outcome irrelevant.

[12] More specifically, the monotone hazard rate assumption specifies that $\frac{\mathrm{d}}{\mathrm{d}p}\left(\frac{g(p)'}{1-G(p)}\right) \geq 0$. This is a common assumption which holds for many distributions including the Normal and the Uniform.

[13] A cost of returning to the original station could easily be added which would decrease the expected value of search but not significantly affect the predictions of the model.

if their expected value of finding a p_2 below p_1 is greater than the cost of searching. This occurs when:

$$\int_{-\infty}^{p_1} (p_1 - p_2) l(p_2) \mathrm{d}p_2 > k.^{14}$$

For simplicity, consumers are assumed not to update their expectations of p_2 after observing p_1. However, under most conditions, if consumers were allowed to update, a prior that is lower than the true price distribution will result in a lower posterior than the posterior resulting from priors equal to the true distribution.[15] In other words, updating after observing p_1 will not effect the results indicating when consumers search *too much* or *too little*.

Define $S(p)$ as the fraction of consumers from one station who choose to search, so that:

$$S(p_1) = G\left(\int_{-\infty}^{p_1} (p_1 - p_2) l(p_2) \mathrm{d}p_2\right).$$

Each consumer has a reservation price above which they will search, and $S(p)$ can be thought of as the c.d.f. of the distribution of these reservation prices. The hazard rate of $S(p)$ has an important significance in this model. One can interpret the hazard rate $\left(\frac{S'(p)}{1-S(p)}\right)$ as the share of the firm's non-searching consumers who choose to search if the firm raises p slightly. For later convenience I define $\phi(p)$ as the inverse hazard rate of $S(p)$.

The relative values of marginal cost, c, and consumers' price expectations, $L(p)$, determine how competitive the market is. As p falls relative to $L(p)$ a greater share of the firm's consumers choose not to search. The firm becomes a monopolist over the demand from its non-searching consumers in the sense that no other firm can steal these customers by offering a lower price. Since $\frac{N}{2}$ customers initially observe each firm's price, the firm's initial demand from non-searching consumers is simply: $x^{ns}(p) = \frac{N}{2}[1 - S(p)]$. Even though consumers have perfectly inelastic demand for the good, the firm's demand from non-searching consumers has elasticity due to the possibility of search. When the firm raises its price, some of its non-searching customers decide to

[14] For simplicity I have not limited the distribution of consumers' expectations to be strictly positive. The simulations in Section 2.1.1 assume that L(p) is normally distributed, which technically allows a positive probability of a negative price. However, this possibility is effectively zero for relevant ranges of prices. A normal distribution with a mean and variance calibrated from actual gasoline price data suggest that the probability of a negative price is on the order of 10^{-179}.

[15] The results of Milgrom (1981) imply that a consumer with a lower (ie. stochastically dominated) prior will have a lower posterior after observing the same signal, as long as the relevant distributions satisfy the monotone likelihood ratio property. This property holds for many common distributions including the Normal, Exponential, Uniform, etc.

search.

The firm also sells to all the searching consumers in the market if it has the lowest price. The total demand for Firm 1 is:

$$x_1(p_1) = \frac{N}{2}\left[1 - S(p_1) + \mathbf{1}(p_1 < p_2)[S(p_1) + S(p_2)]\right]$$

where $\mathbf{1}(p_1 < p_2)$ represents an "indicator function" that equals one if searching consumers choose Firm 1, zero otherwise.

It is necessary to allow for the possibility of mixed strategies. Let $F_i(p)$ represent the distribution function and $f_i(p)$ the density function of Firm i's mixed strategy, with support $[\underline{p_i}, \overline{p_i}]$. Then Firm 1's expected profit given Firm 2's strategy $f_2(p)$ is:

$$\Pi(p_1) = \frac{N}{2}(p_1 - c)\left[(1 - S(p_1)) + \int_{p_1}^{\overline{p_2}} [S(p_1) + S(p_2)] f_2(p_2) \mathrm{d}p_2\right]$$

The expected profit function can be decomposed into a profit function for non-searching consumers and an expected profit function from searching consumers, $\Pi = \Pi^{ns} + \Pi^{s}$ such that:

$$\Pi_1^{ns}(p_1) = \frac{N}{2}(p_1 - c)(1 - S(p_1)) \quad \text{and} \quad \Pi_1^{s}(p_1) = \frac{N}{2}(p_1 - c)\int_{p_1}^{\overline{p_2}} [S(p_1) + S(p_2)] f_2(p_2) \mathrm{d}p_2.$$

A fundamental principle of the model is that p_2 does not affect the profits Firm 1 receives from its non-searching consumers. No matter how aggressively the competition sets prices, Firm 1 can earn positive profits by setting a price so that some of his consumers don't search (as long as c is not too high).

Consider the price, $\tilde{p}$, that maximizes a firm's profits from its non-searching consumers.[16] It is the price that equates the marginal benefit of earning higher profit margins from non-searching consumers with the marginal cost of causing some of your non-searching consumers to search by increasing price. The strategy of maximizing profits from non-search consumers becomes important as an alternative when competing for searching consumers becomes too costly.

When the competing firm is charging a price that is low relative to consumers' expectations, $L(p)$, very few of their consumers choose to search. As a result, pricing below the competing firm does not attract many customers. In other words, the incentive to charge lower prices diminishes as prices fall below expected levels.

[16] $\Pi^{ns}(p)$ is uniquely maximized at $\tilde{p}$ such that $\tilde{p} = \phi(\tilde{p}) + c$. See Lemma 1 in Appendix A for proof.

2.1.1 Equilibrium Prices and Expected Profits

The relative values of marginal cost (c) and consumers' expectations, $L(p)$, affect the nature of the equilibrium. Therefore, the equilibrium prices for a given $L(p)$ are described conditional on the value of c. In the special case where the distribution of search costs are bounded above, there will be some price, p^{as} above which all consumers search. If c is far enough above consumers' expectations so that $c > p^{as}$, all consumers will search and the equilibrium resembles that of a full information, homogeneous product Bertrand model. Proposition 1 reveals that in all other cases only a mixed strategy equilibrium exists. It also describes the support of the mixed strategy equilibrium and the expected profit.

Proposition 1

1. *As long as there are some non-searching consumers (ie. $S(p) < 1$) no pure strategy equilibrium will exist.*
2. *The mixed strategy equilibrium F(p) over support $[\underline{p}, \overline{p}]$ has the following properties:*
   (a) $\underline{p} = \tilde{p}$ *where* $\tilde{p} = \phi(\tilde{p}) + c$
   (b) *Expected profit* $\Pi^* = \frac{N}{2}(\tilde{p} - c)(1 - S(\tilde{p}))$.
   (c) $\underline{p}$ *satisfies the following (for Firm 1):*

$$(\underline{p}_1 - c)\left[1 + \int_{\underline{p}_1}^{\overline{p}} S(p_2) f(p_2) \mathrm{d}p_2\right] = (\tilde{p} - c)(1 - S(\tilde{p}))$$

Proof: See Appendix A.

The intuition for the first result is straightforward. When some consumers are searching and some are not, a firm's best response is almost always to slightly undercut the other firm's price in order to steal the searching consumers. However, at prices close to c, firms are be better off disregarding the searching consumers and raising price to earn higher profits from non-searchers. No pure strategy equilibrium exists since a firm's best response is either to slightly undercut the other firms price or price well above the other firm. This is similar to the mixed strategy equilibrium found in the informed/uniformed consumer model of Varian (1980).

Identifying conditions on the bounds of the equilibrium price distribution is also straightforward. Firms never charge a price greater than the price that maximizes profits from non-searching consumers (ie. $\tilde{p}$), because a firm charging $\overline{p}$ will always have a higher price than its competitor. Therefore, the firm only sells to non-searching consumers and earns the most profit at $p = \tilde{p}$ (by definition). They may charge a lower price if there is some chance that they will attract searching consumers as well. However, they will not charge prices too close to marginal cost since they can always make a positive profit by selling to non-searching consumers only. The expected profit from the mixed strategy equilibrium will be equal to the maximum profits made by selling strictly to non-searching consumers. The lower bound of the distribution, $\underline{p}$, is simply the price at which the firm is indifferent between decreasing price (*undercutting*) to attract all the searching consumers and jumping the price up to $\tilde{p}$ and, in effect, giving up on searching consumers to maximize profits earned from non-searchers.

It is not possible to analytically solve for the entire equilibrium distribution.[17] However, for any particular distributions of consumers' expectations, $L(.)$, and consumers' search costs, $G(.)$, the symmetric mixed strategy equilibrium pricing strategy, $F(p)$, can be calculated numerically. This is possible because the upper bound of the equilibrium price distribution is known. Therefore, the distribution, $F(p)$, can be traced out starting at the upper bound by using the condition that the expected profit at each price must be equal.

I calculate the equilibria for both normally and uniformly distributed consumers' search costs. For comparison I specify the two distributions with similar mean and variance, and I censor each distribution so that they are non-negative with a mass of consumers having zero search costs. Both search cost distributions have a mean of around 3 cents per gallon, a standard deviation near 2, and a 7% mass of consumers with zero search cost. In each case, consumers' priors, $L(p)$, are assumed to be distributed normally.[18] Figure 2, Panels A & B display the resulting equilibria for each level of marginal cost, c, assuming that consumer's expectations about price are held constant with a mean of 80 cents. The shaded regions represent the support of the equilibrium mixed strategy distribution: $[\underline{p}, \overline{p}]$. The solid line within this region represents the mean of the equilibrium price distribution. Figure 3 reports the variance of the equilibrium price distributions

[17] Consequently, the lower bound of the distribution can not be explicitly identified because Firm 1's expected profit from charging $\underline{p}$ depends on how many of Firm 2's consumers are expected to search, which depends on Firm 2's pricing strategy, $F(p_2)$.

[18] For this example, I assume consumers' expectations of the price distribution are distributed normally with a mean of 80 cents and a standard deviation of 5.2 cents.

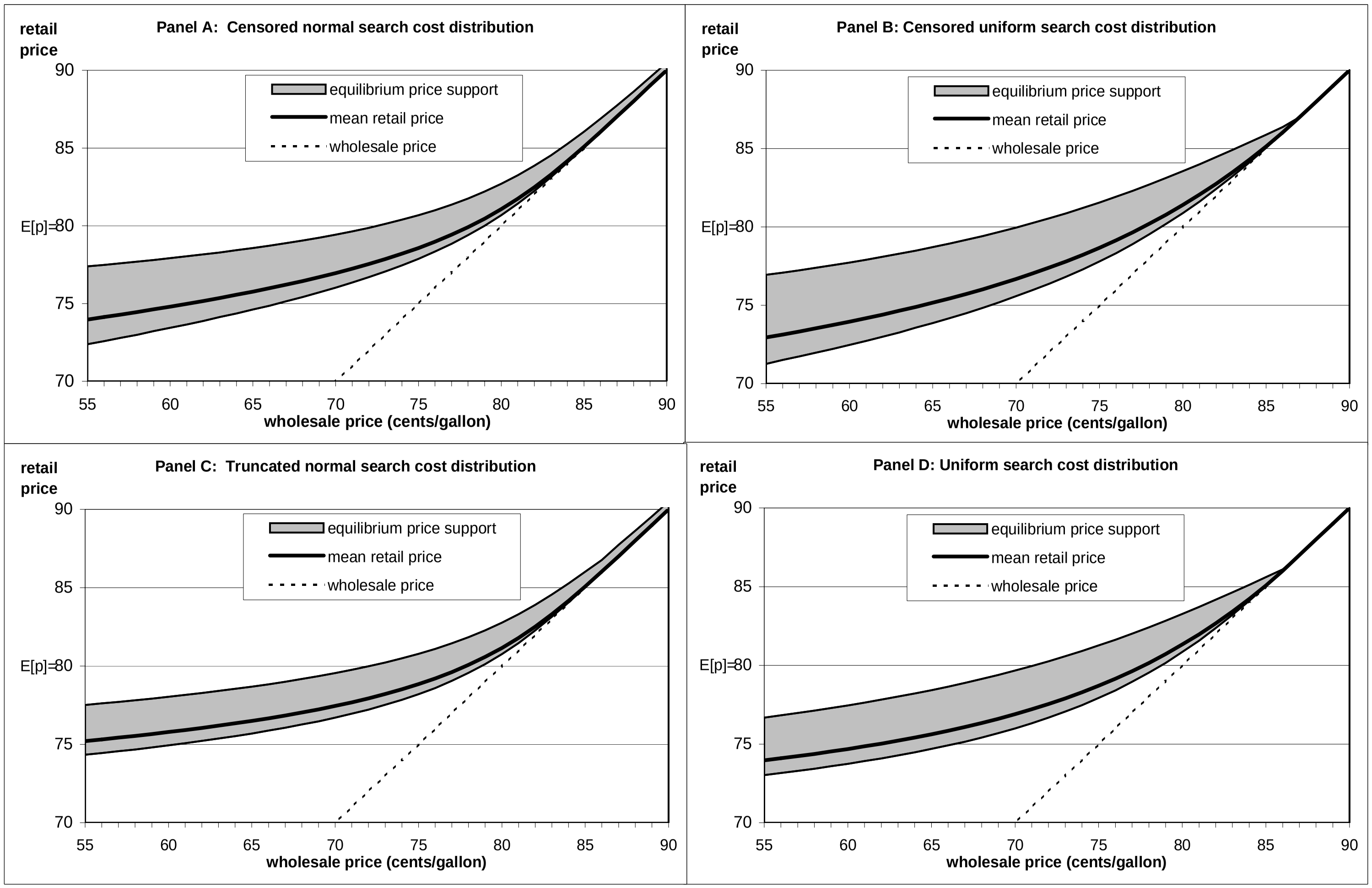
from each of the panels in Figure 2 to illustrate how equilibrium price dispersion is related to marginal costs.

Several important properties of the equilibrium are clearly revealed in Figures 2 & 3. First, equilibrium prices increase with marginal cost, c, when c is high relative to consumers' expectations of price, but prices do not decrease (as quickly) with c when c is much lower than consumers' expectations. When c falls firm's always charge lower prices because the larger profit margin makes it worthwhile to try to attract a few more searching consumers. However, the rate at which a lower price will attract additional consumers falls as prices decline relative to consumers' expectations. This creates a convex relationship between equilibrium prices and marginal costs (for a given level of consumers' expectations). In short, equilibrium prices do not fall significantly once costs are well below consumers' expectations. It is this convex relationship that will generate asymmetric price adjustment when we discuss the dynamic interpretations of reference price search behavior in the next section.

The second important feature of the equilibrium is that prices are more disperse when marginal costs (and prices) are low relative to consumers' expectations. The support of the equilibrium price distribution widens and the variance of prices is higher for low values of marginal cost. When marginal costs are high, many consumers search and the price distribution collapses toward full information perfect competition. When marginal cost is low relative to consumers' expectations of price, firms can charge high margins and still retain lots of non-searching consumers. But going after searching consumers also becomes increasingly attractive as marginal costs become very low. Therefore, price dispersion tends to increase with low costs because firms either charge high margins to non-searchers, or cut prices to go after the few remaining searchers who will still yield fairly high profit margins.

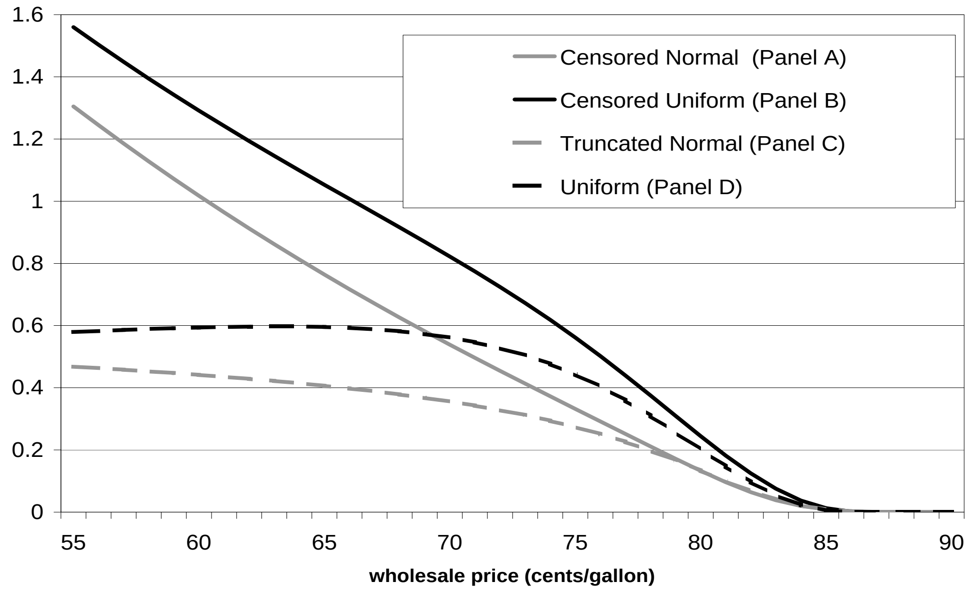
For robustness, I also calculate the equilibria for the extreme case in which there is no mass of consumers with zero search costs. Figure 2, Panels C & D display equilibrium prices when the Normal and Uniform search cost distributions are truncated at zero (rather than censored) so there is no longer a mass of consumers with zero search cost. The basic convex relationship between prices and marginal costs remains similar to Panels A & B, and prices are still more disperse when

Figure 2: Equilibrium Prices for Different States of Wholesale Cost
(Expected Price = 80 cents/gallon)



Panel A: Search costs $k \sim$ CensoredNormal[3,1.95] with $k > 0$. Resulting moments: mean=3.05, SD=1.85.
Panel B: Search costs $k \sim$ CensoredUniform[-0.5,6.5] with $k > 0$. Resulting moments: mean=3.02, SD=2
Panel C: Search costs $k \sim$ TruncatedNormal[3,1.95] with $k > 0$. Resulting moments: mean=3.25, SD=1.73.
Panel A: Search costs $k \sim$ Uniform[0,6.5]. Resulting moments: mean=3.25, SD=1.87.

Figure 3: Variances of the Equilibrium Price Distributions in Figure 2.



marginal costs are below consumers' expectations.[19] However, price dispersion does not grow as much when marginal costs fall in comparison to the case with a mass of informed consumers. In the uniform search cost distribution case, the variance of prices flattens out for very low marginal costs and even starts to fall slightly as marginal costs fall. This occurs because the number of searching consumers left to attract with low prices becomes very small when prices are far below expectations. At some point it becomes more profitable for firms to concentrate more on non-searchers. On the other hand, with even a small mass of zero search cost consumers, the incentive for firms to go after searchers with low prices remains strong. Adding a 1% mass of zero search cost consumers to the above uniform distribution is enough to generate monotonically increasing dispersion as wholesale costs fall. Regardless of the existence of a mass of informed consumers, price dispersion is always higher during periods when marginal costs (and prices) are low relative to expectations.[20]

[19] This sentence corrects a typographical error appearing in the published version.

[20] This relationship holds fairly generally for any search cost distribution containing some consumers with zero or near zero search costs. On the other hand, if consumer search costs were bounded strictly above some positive level, then there exists a price below which no consumers would search. In this case, when wholesale costs are low enough, all firms charge this threshold price and there is no dispersion. This case is discussed in more detail in Lewis (2003). However, I find the case in which search costs for some consumers approach zero to be more realistic and to be a better predictor of observed patterns of price dispersion. (See Section 5.3)

2.2 Dynamic Interpretation and Asymmetric Adjustment

The previous section identifies a simplified static model of competition and consumer search for a particular case where consumers' expectations about prices differ from the actual distribution charged in the market. The results are general in that no assumptions are made about how or why expectations are too high or too low. This section describes a dynamic interpretation of the static equilibrium that is created by assuming that the distribution of consumers' beliefs are formed from past information (i.e. past prices).

For simplicity, a fully dynamic model is not developed. Interpreting the static model in this dynamic sense is, hopefully, a fair approximation given the conditions in this market. Consumers have little ability to optimize purchases over time, given their fairly constant need for gasoline and their relative inability to store. The assumption that firms only maximize current profits eliminates the possibility that firms set prices to influence consumers' expectations (and therefore firm profits) in the future. In reality, this strategic behavior is likely to be limited since there are usually enough stations in any market so that no particular station can significantly affect the expectations of consumers.

When consumers' expectations are higher (lower) than actual prices, the static model predicts that fewer (more) consumers will search. Therefore, the motivation of the simple dynamic model is that if consumers expect prices to be similar to those observed in the past, they will search less when prices are falling and more when prices are rising. Consumers expectations can be represented by any continuous distribution which somehow captures information about prices in previous periods. I assume that a consumer who observes p_1 in period t has a probability distribution function, $B(p_2| \, \hat{p}_{t-1})$, of beliefs about p_2 such that $E[p_2] = \hat{p}_{t-1}$, where $\hat{p}_{t-1}$ is the mean of last period's prices. While this may seem somewhat at odds with the limited information consumers are thought to have about market prices, the assumption simplifies the model so that all consumers have the same price expectations.[21]

[21] An alternative approach could allow heterogeneity in consumers' expectations, possibly based on the price a particular consumer observed in the previous period. Consumers with higher search costs would tend to have higher expectations on price, since they are more likely to have paid a higher price in the previous period. High search cost consumers would end up searching less, low search cost consumers would search more, and the overall effect would be analogous to increasing the variance of the search cost distribution.

The model is also simplified in that the distribution of consumers expectations on price is assumed to change from week to week by shifting up and down with no change in shape. While I believe this assumption to be reasonable approximation of how consumers might behave, it is more restrictive than necessary. Consumers will search less than they would if they knew the true price distribution whenever the expected price distribution stochastically dominates the true price distribution. Therefore, consumers will search more (less) when prices are rising (falling) as long as their expectations are based on past prices in some way such that they are stochastically dominated by (stochastically dominate) the true price distribution.[22]

Recall the two main properties of the equilibrium highlighted in the previous section. For a given level of consumers' expectations: 1) equilibrium prices increase more quickly with wholesale cost as costs rise relative to expectations, and 2) prices exhibit less dispersion as wholesale costs rise relative to expectations. Within the dynamic setting described above, these properties generate three testable implications about how prices respond to wholesale cost changes.

Prediction 1: Given consumers' expectations of prices today, a wholesale cost increase will always result in a larger (in absolute value) movement in the price distribution than an equivalently sized cost decrease would have.

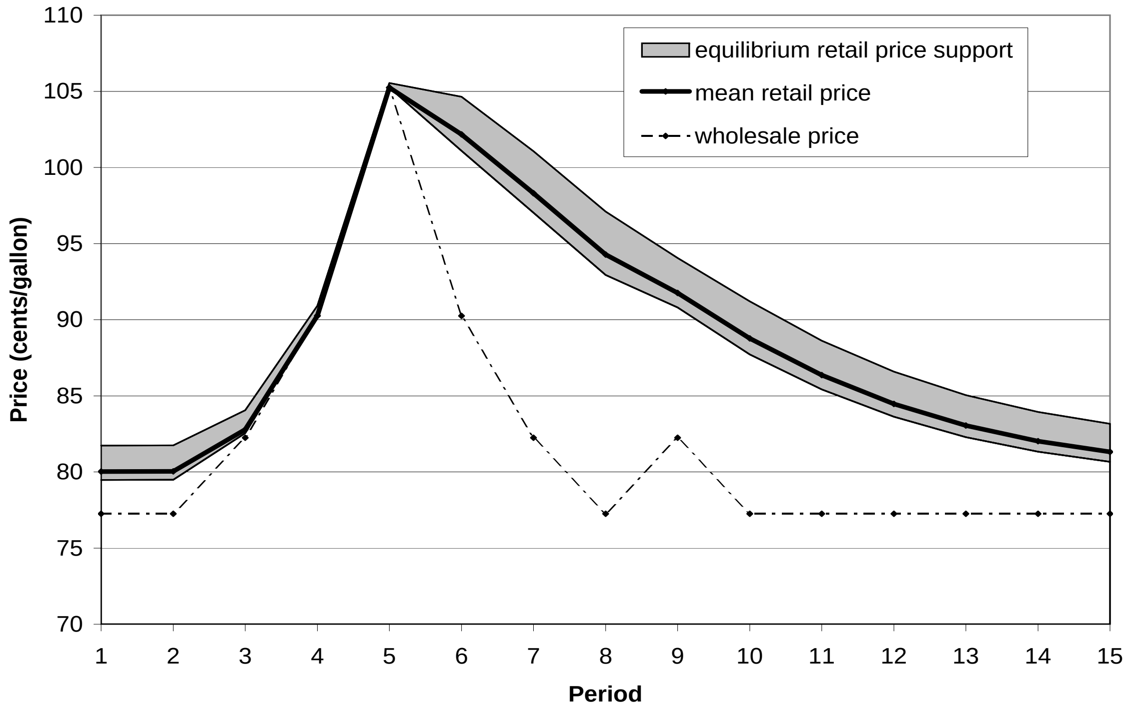
In other words, prices adjust asymmetrically to cost increases and cost decreases. This result follows directly from the convex relationship between wholesale costs and equilibrium prices.

Prediction 2: Given last period's wholesale cost, a change in wholesale cost this period will generate a larger (in absolute value) movement in the price distribution if last period's price distribution was lower.

When last period's prices are high relative to wholesale cost, then consumer's expectations for price this period will also be much higher than cost. Therefore, the equilibrium price will occur in the lower, flatter portion of the static equilibrium $p(c)$ curve depicted in Figure 2, and any change

[22]This would generally be true in observed gasoline markets if consumers' expectations were defined as the observed price distribution from the previous week. Using data from San Diego (described in Section 4) I find that in most cases the price distribution in a given week stochastically dominates or is dominated by the previous week's price distribution in over 90% of observed weeks and in all weeks in which the average price moves by more than .5 cents per gallon.

Figure 4: Simulated Retail Price Response to Changes in Wholesale Price.



in cost will have a relatively small effect on the mean retail price. The implication from this second result is that prices will be less responsive to cost changes when margins are high.[23]

Prediction 3: Price dispersion should be higher when wholesale costs are well below the prices charged in previous periods.

This insight is also fairly straightforward since past prices determine consumers' expectations, and equilibrium price dispersion is higher when marginal cost is low relative to expectations.

In order to illustrate these three properties I construct a hypothetical time series of wholesale cost changes and simulate the resulting equilibrium retail prices predicted by the model. Figure 4 displays the simulated price response when search costs are assumed to be normally distributed across consumers (as they are in Figure 2, Panel A). The shaded region in Figure 4 represents the support of the equilibrium price distribution for each period. The heavy solid line contained in within this support represents the mean of the equilibrium price distribution. The first thing to note is that the response of retail prices to the large (and symmetric) wholesale cost

[23]This sentence corrects a typographical error appearing in the published version.

spike is clearly asymmetric. Rapid cost increases push the margins toward zero and force stations to raise retail prices. On the other hand, the rapid decline in cost is followed by a slower reduction in prices. Firms are discouraged from lowering prices more quickly because very few consumers are searching and so it is difficult to attract more demand by lowering price. The figure also illustrates how prices are less responsive to cost changes when margins are high. A small increase in cost is included in Period 9 that matches the increase in Period 3. In Period 3, margins are lower and prices increase significantly with the change in cost. However, in Period 9 margins are much higher and the response of price to the cost increase is smaller. Finally, the range of prices observed clearly shrinks when prices are increasing and widens when prices are falling.

3 Alternative Explanations of Asymmetric Price Adjustment

In their seminal article on asymmetric price adjustment Borenstein et al. (1997) propose two commonly cited explanations for the asymmetric adjustment of retail gasoline prices: one based on consumer search and the other on "focal price" tacit collusion. The first explanation notes that a particular dynamic interpretation of the search model of Benabou and Gertner (1993) may be consistent with asymmetric price adjustment. Models by Tappata (2009) and Yang and Ye (2008) have since attempted to formalize this asymmetric adjustment result using a dynamic process of marginal cost shocks similar to those in Benabou and Gertner (1993). These search models are similar to the reference price search model in that fluctuations in search activity associated with price changes lead prices to adjust asymmetrically. However, as discussed in Section 1, more specific predictions of these models differ from those of the reference price search model. Since the Tappata (2009) and Yang and Ye (2008) models have only two marginal cost states (high and low), it is difficult to distinguish predictions about the speed of price response during high and low margin periods from prediction about response to positive and negative cost changes. However, generalizing the intuition of these models to more cost states appears to generate predictions opposite those of the reference price search model. In the Tappata (2009) and Yang and Ye (2008) models, more search and faster price response occur when dispersion is largest, and dispersion is inversely related to marginal cost.[24] Therefore, a more generalized version of these models would predict that prices respond more quickly to cost changes when margins are high than when they are low. This contradicts *Prediction 2* of the reference price search model.

The second explanation suggested by Borenstein et al. (1997) was a "focal price" tacit collusion theory in which firms avoid a coordination problem by using past prices as a focal price at which to collude. When wholesale costs fall, collusion is easier to sustain because firms can coordinate by simply not changing their price. Decreases in cost provide an opportunity for competing firms to begin colluding. In contrast, firms would immediately raise prices in response to cost increases, since continuing to charge past prices would be unprofitable. Asymmetric adjustment results because collusion delays price reductions but not price increases.

No rigorous model of focal price collusion has been specified, and testing against the predictions of a super-game model of tacit collusion is difficult since there are an infinite number of equilibrium price paths. Nevertheless, there is a fairly specific price pattern suggested by the notion that colluding on past prices provides a mechanism for firms to coordinate. We should observe firms sticking to a past price level following a decrease in cost until a point at which collusion breaks down and prices fall. Interestingly, during periods when margins are already high because firms are sticking to a past price level, prices may be relatively unresponsive to a cost change. This is similar to the behavior suggested by *Prediction 2* of the reference price search model.

However, if focal price collusion breaks down simultaneously for all firms in the market, the average price would eventually fall very rapidly to competitive levels. This differs from the slow gradual response of prices predicted by the reference price search model and generally observed in the data.[25] Alternatively, if smaller submarkets are colluding separately, collusion in some submarkets may breakdown earlier causing some prices in the market to fall before others and producing a more gradual decline in the average market price. As average prices decline, firms with the highest prices in the city would still be colluding at past prices, while firms with the lowest prices would have broken from collusion and would be pricing much more competitively.

[24] In the Tappata (2009) and Yang and Ye (2008) models, equilibrium price dispersion is decreasing in the marginal cost because the possible support of prices shrinks as the cost moves up toward consumers' choke price.

[25] See the gradual price declines in Figures 1 and 4

Therefore, the lowest prices in the market should fall more quickly and adjust much more to changes in price, as they would in a competitive market. There is no such prediction in the reference price search model where the lowest prices in the market respond to cost changes much like the rest of the price distribution (see Figure 4).

Submarkets breaking from focal price collusion at different times could also generate increased citywide price dispersion following a decrease in cots just like in the reference price search model. However, unlike in the reference price search model, this increase in price dispersion should occur exclusively between localized submarkets and not within submarkets, whereas a decline in search activity in the reference price search model would predict increased dispersion among all stations (even within submarkets). Therefore, I will empirically examine the response behavior of the lowest prices in the market and the nature of price dispersion during high margin periods to test between the predictions of the focal price collusion and reference price search models.

4 Data

Most of the previous research on asymmetric gasoline price adjustment has examined patterns in city or state average retail and wholesale price data. In addition, prices are sometimes observed relatively infrequently (monthly or biweekly) or are limited to a relatively short time period. I utilize two different sources of retail price data to alleviate some of these shortcomings. The first contains station-specific weekly retail price data from 369 gas stations in the San Diego area have been collected from January 2000 to December 2001 by the Utility Consumer Action Network. Prices are collected each Monday morning by designated observers who physically observe and record prices of station signs. The sample of stations represents roughly 50% of the 735 gasoline stations in San Diego County.[26] Unfortunately, prices are not observed for every station in every week. However, the price information is fairly complete, with over 62% of stations having 5 or fewer missing price observations during the 93 week sample period. Unlike most previous studies, these data provide the opportunity to compare differences in prices and price adjustment behavior

[26]The total number of stations is taken from a census of San Diego gas stations conducted by Whitney Leigh Corporation in September of 1998.

across stations over time. However, for studying overall patterns of price adjustment dynamics the two year sample period is less than ideal. Therefore, I also use a longer time series of citywide average weekly retail gasoline prices. Unfortunately, prices for San Diego are unavailable, but prices for nearby Los Angeles have been collected and reported by the Department of Energy's Energy Information Administration from June 2000 to July 2007. Each week the agency reports an average price based on a citywide telephone survey of gas stations performed every Monday morning. These data provide a much longer sample period to better observe the dynamic properties of price adjustment in the region.

Los Angeles "spot market" gasoline prices, also collected by the Department of Energy over the same time period, are used as wholesale prices for both the San Diego and Los Angeles markets. This series represents the price of generic gasoline on the west coast and is calculated from a daily survey of major traders. Weekly wholesale prices are calculated as the average spot price over the week prior to each retail price observation. This is used as marginal cost because it is essentially the opportunity cost of keeping gas for your station instead of selling it to other wholesalers.

Though gas stations sometimes have different operational or contractual structures I will assume that all stations behave as if they are maximize profits with a marginal cost equal to the spot market price. For an independent (unbranded) station the interpretation is straightforward. Station owners buy unbranded gasoline for their station at the wholesale market price and sell the gasoline at whatever price they choose. Alternatively, branded stations sell gasoline under a parent company's brand name. Some branded stations are owned and directly operated by the parent company. The parent company faces the same profit maximizing decision for each of these stations as an unbranded station would. Other branded stations are run by lessee-dealers who operate the station independently, but are required to buy gasoline from their parent company. The parent company determines the wholesale price which generally differs across stations within the brand. In addition, parent companies charge fees, set quantity requirements, and offer volume discounts for their lessee-dealers which also vary across stations. These parameters allow the parent company to very effectively extract most of the rents from their franchise stations. Therefore, the parent company maximizes profits for the station; effectively determining a retail price by setting the wholesale transfer price and franchise fees. If the parent company were not able to extract all these rents, double marginalization might be observed at lessee-dealer stations. However, evidence suggests little difference between the pricing behavior of company operated and lessee-dealer stations.[27] The lack of observed double marginalization suggests that all stations price as if profits were being maximized by a single firm given the wholesale cost of gasoline. Although a large parent company might be maximizing profits for many stations, these stations are generally not located in the same area. Branded stations experience effectively no competition from other stations of the same brand.

Graphs of the full time series of average prices from both the Los Angeles and San Diego data are presented in Figures 9 and 10. The reported average retail price for Los Angeles during the first 6 to 12 months of the sample appears unusually low relative to wholesale cost. Comparisons with price reports from other sources during this period suggest the Department of Energy's retail average for Los Angeles may be somewhat inaccurate, but this is not certain. Empirical estimates of pricing behavior are slightly more precise when data from this period are excluded. However, for robustness, the empirical results reported in the remainder of the paper are estimated using the full sample.

5 Empirical Analysis

The goal of the empirical analysis is to test some of the predictions of the reference price search model and to identify whether this model can explain observed pricing behavior better than some of the alternative theories. I accomplish this using three different empirical exercises, each corresponding to a particular difference in the predictions of the alternative theories. First I estimate the speed of retail price response to wholesale cost shocks using the 8 years of Los Angeles average price data. Specifically, I want to test whether prices respond to cost changes more quickly when

[27]Hastings (2004) provides evidence that the organizational structure of a branded station (company operated vs. lessee-dealer) has no significant effect on the local market price. In addition, average margins in my data set are only slightly higher (1.5 cents) at lessee-dealer than at company operated stations. This number is fairly small compared to overall margins which average around 16 cents. However, this figure is subject to the unobserved, systematic process by which a station is established as a company-op or lessee-dealer. Most importantly, during times when overall margins increased in my sample, margins at lessee-dealer stations did not increase significantly more rapidly than at company operated stations as one might expect if double marginalization was occurring only at lessee-dealer stations. This is even true for lessee-dealer stations with no nearby competitors (within a mile).

margins are low than when they are high.[28] This pattern is predicted by the reference price search model and the focal price collusion models but contradicts the predictions of the search models of Tappata (2009) and Yang and Ye (2008). I next use the station level San Diego price data to estimate whether the lowest prices in the city each week respond more quickly and less asymmetrically to cost changes than rest of the price distribution. This pattern would be predicted by the focal price collusion model if the lowest prices during high margin periods represent stations in submarkets that have broken from collusion earlier. Finally, I examine whether price dispersion in the San Diego area is higher during high margin periods after costs fall than during low margin periods when costs and prices are increasing as predicted by the reference price search model and the Tappata (2009) and Yang and Ye (2008) models. The focal price collusion theory may have a similar prediction for citywide price dispersion, but has the opposite prediction when applied to localized groups of stations, since high margins result from local competitors who are colluding and should have similar pricing behavior.

5.1 Price Response to Cost Changes

The reference price search model predicts that prices respond less to cost changes while margins are high. Such behavior is consistent with the asymmetric response to positive and negative cost changes that has been well established by previous empirical studies. Prices may adjust faster to cost increases simply because when costs rise firms are more likely to have low margins. Conversely, firms are more likely to respond slowly after a cost decrease because they are more likely to have higher margins. However, the reference price search model also predicts that firms respond less to cost increases (or decreases) when margins are high than when margins are low. This behavior has not been well studied because the dynamic models used in previous empirical studies (e.g. Borenstein, Cameron and Gilbert (1997)) did not allow this type of asymmetry. The following empirical analysis suggests that the level of margins may have a more significant effect on response behavior than the direction of the cost change.

[28] This sentence corrects a typographical error appearing in the published version.

5.1.1 Empirically Modeling the Dynamic Price-Cost Relationship

The starting point for this analysis is to econometrically model the dynamic processes which describe the relationship between retail and wholesale gasoline prices. I initially focus on average price response behavior using the Los Angeles average retail price data set because it provides a much longer sample with which to empirically identify patterns over time. The ultimate goal is to estimate how current and future prices respond to a change in cost. Dickey-Fuller tests of retail prices and wholesale cost cannot reject nonstationarity in my sample. Furthermore, an Augmented Dickey-Fuller type cointegration test based on Engle and Granger (1987) suggests that prices and cost are cointegrated. As a result, I estimate an error correction model using the procedures of Engle and Granger (1987) and Stock (1987).[29]

The basic model is the following:

$$\Delta p_t = \sum_{i=0}^{I-1} \beta_i \Delta c_{t-i} + \sum_{j=1}^{J-1} \gamma_j \Delta p_{t-j} + \theta \left[p_{t-1} - (\alpha + \phi c_{t-1})\right] + \epsilon_t \qquad (1)$$

where:

$$\Delta p_t = p_t - p_{t-1} \qquad \text{and} \qquad \Delta c_t = c_t - c_{t-1}$$

$$E(\epsilon_t) = 0 \qquad \text{and} \qquad Var(\epsilon_t) = \sigma_t^2$$

The first two terms can be interpreted as estimating short run dynamics and the parameter θ measures the percentage of per period price reversion to the long run relationship specified by: $p_t = \alpha + \phi c_t$.

I use the coefficient estimates to calculate *cumulative response functions* (CRFs). These CRFs predict the response path of price to a one unit change in cost. The predicted effect on price n periods after a cost change includes the direct effect of the past cost change (β_{t-n}), plus the indirect effects from the resulting price changes in the previous $n-1$ periods (γ_j's), and the error correction effect.[30] These CRFs allow observed response behavior to be easily compared with that predicted by the theoretical models.

[29] This basic approach is similar to Borenstein et al. (1997) and typical of the empirical literature on asymmetric price adjustment.

[30] CRFs are calculated by the method specified in the Appendix of Borenstein et al. (1997)

5.1.2 Nonlinearities and Estimation Technique

The linear model above predicts identical responses to all changes in cost. To test the theoretical implication that price is more responsive to cost changes when profit margins are low, I relax the linearity assumption by allowing the coefficients to be estimated separately for periods of "high" and "low" margins. Response behavior can then be estimated separately for each regime, and tests can identify if these estimates significantly differ.

The error correction model suggests a natural way to identify "high" and "low" margin periods based on the long run relationship between p and c. Following Engle and Granger (1987) and Stock (1987) I utilize a two stage estimation procedure. First the long run relationship between p_t and c_t implied in the error correction term is estimated from the following regression:

$$p_t = \alpha + \phi c_t + \eta_t. \tag{2}$$

The lagged error term (η_{t-1}) from this regression can replace the error correction term in the estimation of Equation (1). Due to superconsistency the first stage residual ($\hat{\eta}_{s,t-1}$) can be used as the "true" value in the second stage and no standard error corrections are necessary. In addition, since the long run relationship is identified in the first stage, the sample can be divided into high and low margin periods based on $\hat{\eta}_{t-1}$. This is commonly referred to as a threshold autoregressive model (see Enders and Granger(1998)).

The resulting model is:

$$\Delta p_t = \begin{cases} \sum_{i=0}^{I-1} \beta_i^{hm} \Delta c_{t-i} + \sum_{j=1}^{J-1} \gamma_j^{hm} \Delta p_{t-j} + \theta^{hm} \eta_{t-1} + \epsilon_t & : \quad \eta_{t-1} > \lambda \\ \sum_{i=0}^{I-1} \beta_i^{lm} \Delta c_{t-i} + \sum_{j=1}^{J-1} \gamma_j^{lm} \Delta p_{t-j} + \theta^{lm} \eta_{t-1} + \epsilon_t & : \quad \eta_{t-1} < \lambda \end{cases} \tag{3}$$

where η_{t-1} is the residual from the OLS estimation of Equation (2), and λ is the threshold parameter.

The coefficients of Equation (3) are estimated separately for high margin ($\eta_{t-1} > \lambda$) and low margin ($\eta_{t-1} < \lambda$) periods. The behavior estimated by the high margin coefficients describes the response of p to a change in c when p is high relative to it's long run equilibrium level. Following Hansen (2000), the threshold parameter λ is selected to minimize the sum of squared residuals ϵ_t.[31]

Endogeneity may be a concern since Δc_t will be correlated with ϵ_t if unexpected retail price shocks in the current period feed back into the wholesale price. Fortunately, I have good instruments available for wholesale gasoline prices. Crude oil prices are obviously highly correlated with gasoline prices. However, oil prices are largely determined in a worldwide oil market and many different products are produced from crude oil. For these reasons, changes in the price of gasoline in California are not likely to have much of an effect on world oil prices. Furthermore, changes in oil price should only affect retail gasoline prices through the wholesale gas price. Therefore, an oil price series such as the West Texas Intermediate crude price provides an ideal instrument. [32]

Seven lags of cost and four lags of price are included in the estimation of Equation (3). These lag lengths are similar to those used in previous studies (1-2 months), and the estimates are fairly robust to changes in lag length specification.[33] To test for the exogeneity of cost in Equation (3), I estimate the model using instrumental variables and OLS.[34] Current and 3 periods of lagged West Texas crude oil prices changes are used as instruments for the current change in wholesale gasoline price. Both a Hausman test and an augmented regression test are unable to reject the exogeneity of Δc_t above the 48% significance level. Therefore, my analysis will concentrate on the results of the OLS estimation.

The estimated coefficients from the model in Equation (3) are reported in the first column of Table 1. As expected, early lags and error correction coefficients are the most precisely esti-

[31] The value of λ that minimizes the sum of squared residuals in Equation 3 is $\lambda = 2.5$, which implies that prices are in a high margin regime during 37% of observed weeks, and a low margin regime during 63% of the weeks. A likelihood ratio test proposed by Hansen (2000) suggests that values of λ in the range $[1.5, 13.5]$ can not be rejected at the 95% level. While this range is somewhat large, only 23% of observed values of η_t fall within this range. More importantly, coefficients and response functions estimates are fairly insensitive to the value of λ within this range. Even when estimating the model using $\lambda = 13.5$ coefficients are similar to those presented here and actually imply a slightly higher level of asymmetry in price response.

[32] I am implying the existence of a second equation in the model as follows (with r_t representing crude oil prices):

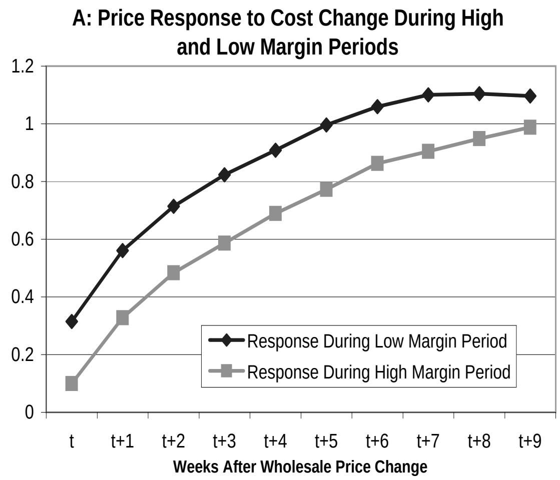
$$\Delta c_t = \sum_{i=0}^{I-1} \eta_i \Delta r_{t-i} + \sum_{j=1}^{J-1} \xi_j \Delta c_{t-j} + \lambda \left(c_{t-1} - \zeta r_{t-1}\right) + \nu_t.$$

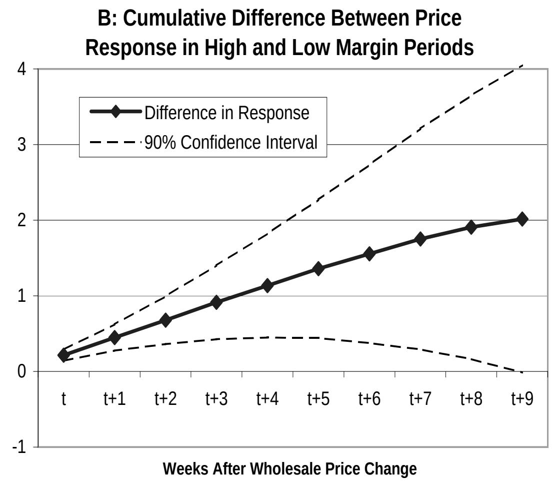
If ν_t is correlated with ϵ_{st} from the price equation then IV would be necessary to estimate β_0 consistently.

[33] Additional lags continue to be significant when included (even for well above 10 lags), however additional lags sacrifice degrees of freedom and appear to have very little effect on the estimates of price response.

[34] Robust standard errors are constructed to account for possible heteroscedasticity.

Figure 5: Cumulative Response Functions from Estimation of Equation 3





mated. There are some clear differences between the coefficients corresponding to high and low margin periods. For example, during low margin periods 31.5% of a change in wholesale cost is passed through to the retail price in the first week, whereas only 10% of the change is passed through during high margin periods. The best way to understand the overall significance of these results is to examine the implied CRFs and tests for differences.

Figure 5a presents the estimated CRFs during high and low margin periods. Recall that the CRF describes the cumulative proportional response of price in each period following a one unit change in cost in period t. The low margin CRF lies above the high margin CRF indicating that price responds more rapidly to a cost shock during a period of low margins than during a period of high margins. The CRF equals 1 when the cost change has been fully passed through to price. The low margin CRF approaches 1 much more quickly than the high margin CRF. Standard errors for these response functions are estimated using the delta method. The cumulative difference between these two response functions is also reported in Figure 5b and is significant until the ninth week following the shock. The cumulative difference at period n is the sum of the differences of the two CRFs over the previous n periods. This represents the total difference in price paid (cents/gallon) from what would have been paid if price adjusted at the speed estimated in the other regime. For example, over the adjustment period a 10 cent increase in wholesale price during a low margin period would cost a 10 gallon/week consumer over $2.00 more than a 10 cent increase during a high margin period. These results are consistent with the prediction of the reference price search model. Prices are more responsive to cost when margins are low than when margins are high.

Table 1: Coefficient Estimates for Equations 3 & 4

	Equation 3		Equation 4			
			Positive Change		Negative Change	
	(1)		(2)		(3)	
$\Delta\text{Wholesale}_{t}^{lm}$	0.315^{***}	(0.020)	0.353^{***}	(0.036)	0.276^{***}	(0.046)
$\Delta\text{Wholesale}_{t-1}^{lm}$	0.129^{***}	(0.033)	0.128^{**}	(0.063)	0.143^{**}	(0.064)
$\Delta\text{Wholesale}_{t-2}^{lm}$	0.073^{*}	(0.040)	0.094	(0.067)	0.031	(0.061)
$\Delta\text{Wholesale}_{t-3}^{lm}$	0.036	(0.028)	0.010	(0.045)	0.069	(0.050)
$\Delta\text{Wholesale}_{t-4}^{lm}$	0.056^{**}	(0.026)	0.080^{*}	(0.047)	0.037	(0.041)
$\Delta\text{Wholesale}_{t-5}^{lm}$	0.071^{***}	(0.025)	0.089^{**}	(0.040)	-0.015	(0.050)
$\Delta\text{Wholesale}_{t-6}^{lm}$	0.045	(0.029)	0.025	(0.054)	0.069	(0.045)
$\Delta\text{Wholesale}_{t-7}^{lm}$	0.031	(0.028)	-0.002	(0.043)	0.054	(0.054)
$\Delta\text{Retail}_{t-1}^{lm}$	0.267^{***}	(0.076)	0.231^{**}	(0.093)	0.416^{*}	(0.246)
$\Delta\text{Retail}_{t-2}^{lm}$	-0.016	(0.085)	-0.027	(0.100)	-0.020	(0.192)
$\Delta\text{Retail}_{t-3}^{lm}$	0.074	(0.073)	0.032	(0.083)	0.201	(0.171)
$\Delta\text{Retail}_{t-4}^{lm}$	-0.074	(0.068)	-0.051	(0.101)	-0.129	(0.169)
$\Delta\text{Wholesale}_{t}^{hm}$	0.100^{***}	(0.031)	0.218^{***}	(0.056)	-0.002	(0.047)
$\Delta\text{Wholesale}_{t-1}^{hm}$	0.134^{***}	(0.036)	0.007	(0.068)	0.158^{***}	(0.040)
$\Delta\text{Wholesale}_{t-2}^{hm}$	0.042	(0.027)	0.028	(0.029)	0.117^{***}	(0.038)
$\Delta\text{Wholesale}_{t-3}^{hm}$	-0.014	(0.025)	0.009	(0.048)	0.019	(0.038)
$\Delta\text{Wholesale}_{t-4}^{hm}$	0.003	(0.028)	0.025	(0.041)	0.044	(0.036)
$\Delta\text{Wholesale}_{t-5}^{hm}$	-0.008	(0.025)	-0.025	(0.029)	0.062	(0.038)
$\Delta\text{Wholesale}_{t-6}^{hm}$	0.018	(0.025)	0.059^{*}	(0.033)	-0.003	(0.035)
$\Delta\text{Wholesale}_{t-7}^{hm}$	-0.014	(0.017)	-0.007	(0.027)	-0.033	(0.021)
$\Delta\text{Retail}_{t-1}^{hm}$	0.164^{*}	(0.087)	0.183	(0.278)	0.054	(0.105)
$\Delta\text{Retail}_{t-2}^{hm}$	0.193^{***}	(0.053)	0.110	(0.098)	0.176^{*}	(0.095)
$\Delta\text{Retail}_{t-3}^{hm}$	0.032	(0.055)	0.045	(0.063)	-0.019	(0.104)
$\Delta\text{Retail}_{t-4}^{hm}$	0.108^{*}	(0.060)	0.005	(0.070)	0.338^{***}	(0.106)
Error Correction Term^{hm}	-0.088^{***}	(0.023)		-0.056^{**}	(0.024)	
Error Correction Term^{lm}	-0.048^{**}	(0.023)		-0.045	(0.034)	
R^2	0.758			0.775		
obs	368			368		

Dependant Variable: Weekly change in retail price (ΔRetail_t)

Robust standard errors are in parenthesis

***, **,and * indicate statistical significance at the 1%, 5%, and 10% levels.

5.1.3 Refinements to the Nonlinear Structure

Unlike the analysis above, previous empirical studies of asymmetric adjustment have directly estimated separate price response functions for cost increases and decreases. Without considering margin size, these results generally indicate that price responds more rapidly to cost increases than cost decreases. The model in Equation (3) does not explicitly allow different price response behavior based on the direction of the cost change. Therefore, this section continues the above analysis while explicitly allowing for asymmetric response to positive and negative cost changes. This further relaxes the linearity of the estimation and helps to more accurately compare results with previous empirical findings and theoretical predictions.

The estimation of Equation (3) in the previous section assumes that price responds identically to all cost changes while margins are high (or when margins are low). The CRF for a high margin cost change is estimated from both positive and negative cost changes. If p responds differently to positive and negative cost changes within the high margin regime then the model in Equation (3) is misspecified.

To relax this assumption, separate coefficients can be estimated for positive and negative observations of each lagged cost and price change[35]:

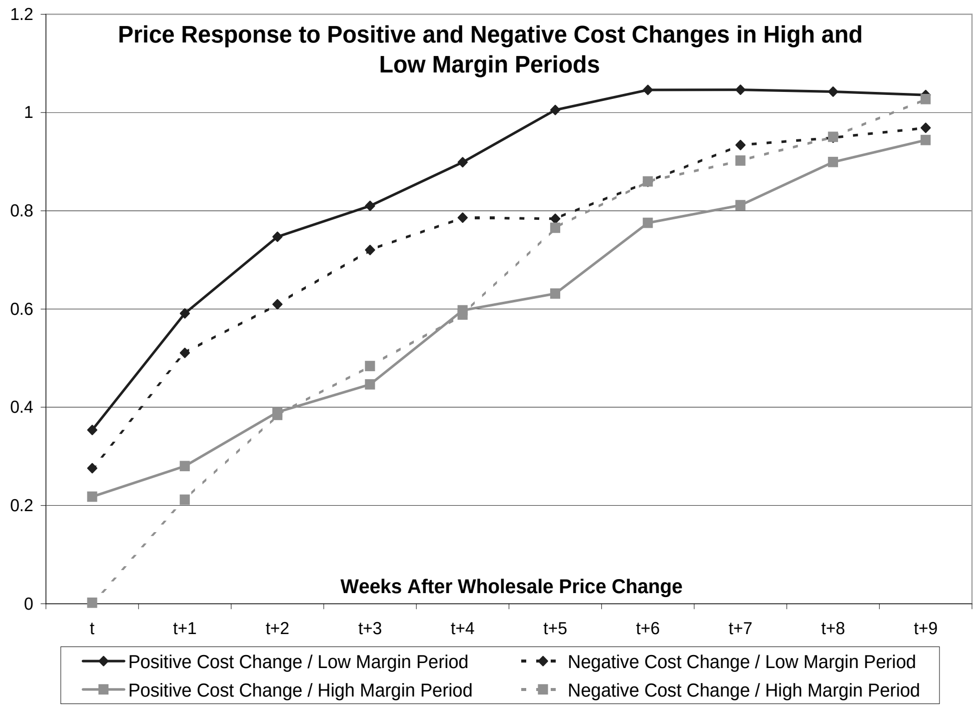
$$\Delta p_t = \begin{cases} \begin{array}{l} \sum_{i=0}^{I-1}(\beta_i^{+,hm}\Delta c_{t-i}^{+} + \beta_i^{-,hm}\Delta c_{t-i}^{-})+ \\ \qquad \sum_{j=1}^{J-1}(\gamma_j^{+,hm}\Delta p_{t-j}^{+} + \gamma_j^{-,hm}\Delta p_{t-j}^{-}) + \theta^{hm}\eta_{t-1} + \epsilon_t \end{array} & : \quad \eta_{t-1} > \lambda \\ \begin{array}{l} \sum_{i=0}^{I-1}(\beta_i^{+,lm}\Delta c_{t-i}^{+} + \beta_i^{-,lm}\Delta c_{t-i}^{-})+ \\ \qquad \sum_{j=1}^{J-1}(\gamma_j^{+,lm}\Delta p_{t-j}^{+} + \gamma_j^{-,lm}\Delta p_{t-j}^{-}) + \theta^{lm}\eta_{t-1} + \epsilon_t \end{array} & : \quad \eta_{t-1} < \lambda \end{cases} \tag{4}$$

Using this model, separate CRFs can be identified to describe how prices during high or low margin periods respond to positive or negative cost changes.[36] Equation (4) is estimated by OLS in the same manner as Equation (3). Coefficient estimates are reported in columns 2 & 3 of Table 1, and the resulting CRFs are reported in Figure 6. Once again, a Hausman exogeneity test of the current value of cost can not be rejected.

[35] $\Delta c_{t-i}^{+} = \max(\Delta c_{t-i}, 0)$ and $\Delta c_{t-i}^{-} = \min(\Delta c_{t-i}, 0)$. Same for price change variables.

[36] To be clear, the high margin CRF for a positive cost change is identified by the relationship between a price change in a high margin period and current and/or past positive cost changes. Certainly, positive cost changes tend to lead to lower margins, so there are fewer (but still enough) observations to identify the high margin/positive (and low margin/negative) CRFs.

Figure 6: Cumulative Response Functions from Estimation of Equation 4

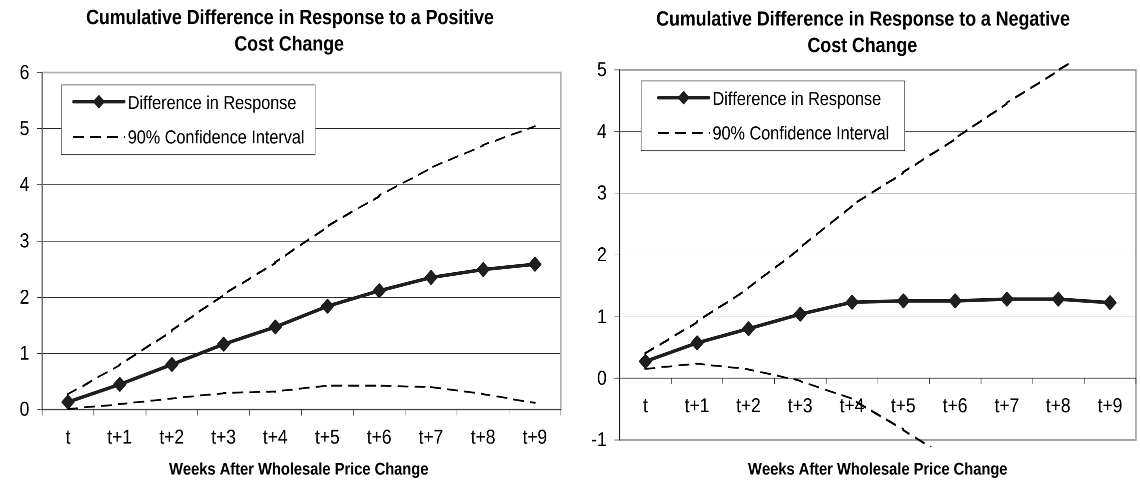


These results continue to suggest that prices respond more quickly in low margin periods than in high margin periods.[37] The difference in the estimated speed of response during high and low margin periods to a positive cost change is even larger than the difference estimated in Figure 5 for a generic price change. In addition, the difference between high and low margin periods in the response to a negative cost change is similar to the difference estimated in Figure 5 for a generic price change, at least for the first five weeks following the cost change. The cumulative difference in response to a negative cost change during high and low margin periods is significantly different from zero at the 90% level for the first 4 weeks following the change. A Wald test of the equivalence of the models in Equations (3) and (4) can be overwhelmingly rejected at the 1% level, suggesting that estimating response behavior with separate coefficients for positive and negative cost changes is more accurate. In addition, Equation (4) allows for examination of response asymmetries between positive or negative changes within either high or low margin periods.

The previous empirical literature on asymmetric gasoline price adjustment has estimated more rapid responses to increases in cost than to decreases. However, these studies do not sepa-

[37]This sentence corrects a typographical error appearing in the published version.

Figure 7: Cumulative Difference Between Price Response in High and Low Margin Periods



rately examine periods with high and low margins. My results suggest that, in fact, responses to positive cost changes appear faster largely because positive cost changes tend to lead to periods of low margins. After controlling for the size of profit margins, I find very little evidence that prices respond more quickly to increases in cost than to decreases. As the results in Figure 6 suggest, during low margin periods prices respond only slightly faster to a positive cost change than to a negative change. This difference is not statistically significant. During high margin periods, responses to cost increases are faster only in the first two weeks.[38] Beyond two weeks after the cost change the response to a cost increase is the same or slower than that for a cost decrease. The profit margins being earned in the market seem to be a stronger determinant of the speed of price response than the direction of the cost change. Previous empirical studies of asymmetric adjustment could not identify this result while assuming an identical response to all cost changes of the same sign. Overall, the pricing behavior identified mirrors that predicted by the reference price search model.

5.2 Station Price Reductions

While the reference price search model gives general predictions about how all firms' prices should respond to cost shocks, the focal price collusion theory suggests that prices of some stations should fall more quickly after a fall in cost as collusion in different submarkets breaks down earlier than in others. I am able to test for differences in the speed of price reductions with a city using station

[38]This sentence corrects a typographical error appearing in the published version.

specific retail price data from San Diego during 2000 and 2001.

If asymmetric adjustment results from focal price collusion, then during periods of high margins and falling prices the lower tail of the price distribution should represent stations that have already broken from collusion and are pricing relatively competitively. Therefore, the response of the lowest prices in the city to cost decreases should be similar to that for cost increases when there is also no collusion occurring. In comparison, prices higher up in the citywide distribution should respond more slowly to cost decreases since these prices represent colluding stations. To empirically examine these differences I calculate several percentiles of the price distribution in each week and construct a time series of each percentile over the sample period. This enables me, for example, to compare how the 5th percentile of the price distribution fluctuates over time in comparison to the median price in the distribution.

To more accurately capture whether a particular station's price is unusually high or low I also want to control for possible differences across stations in convenience or amenities that allow stations to consistently charge more or less than others on average. I measure a station's relative attractiveness by averaging over time the difference between the station's price and the citywide average price for the week. I then construct an adjusted price distribution for each week using each station's price minus its average price premium.[39]

For selected percentiles of the adjusted price distribution I estimate price response functions to test whether lower percentiles of the citywide distribution tend to respond more symmetrically to cost shocks than the rest of the distribution. As in the previous section, I use Equation (3) to separately identify price response in periods when the average profit margin is lower or higher than normal. In this case, however, the model must be estimated from a shorter time series than when using the Los Angeles average data. For this reason it is not feasible to estimate as many lags in the error correction model as are estimated in Section 5.1.2. Instead I estimate the model with 3 lagged changes in cost and 2 lagged changes in price. The regression results for the median price and the 10th, 5th, and 2nd percentile prices are presented in Table 2.

The coefficient estimates from each of the price regressions are fairly similar across the different percentiles. More importantly, the predicted speed of price response implied by the coefficients for the different percentiles are nearly identical. The estimated CRFs constructed from each percentile regression are presented in Figure 8.[40] It appears that the lowest prices

[39]A station's final adjusted price in a given week would be constructed as follows: $p_{st}^{adj} = p_{st} - \frac{1}{T}\sum_{t=1}^{T}\left(p_{st} - \frac{1}{S}\sum_{s=1}^{S} p_{st}\right)$

[40]These estimates of price response during both high margin and low margin periods are somewhat slower than the

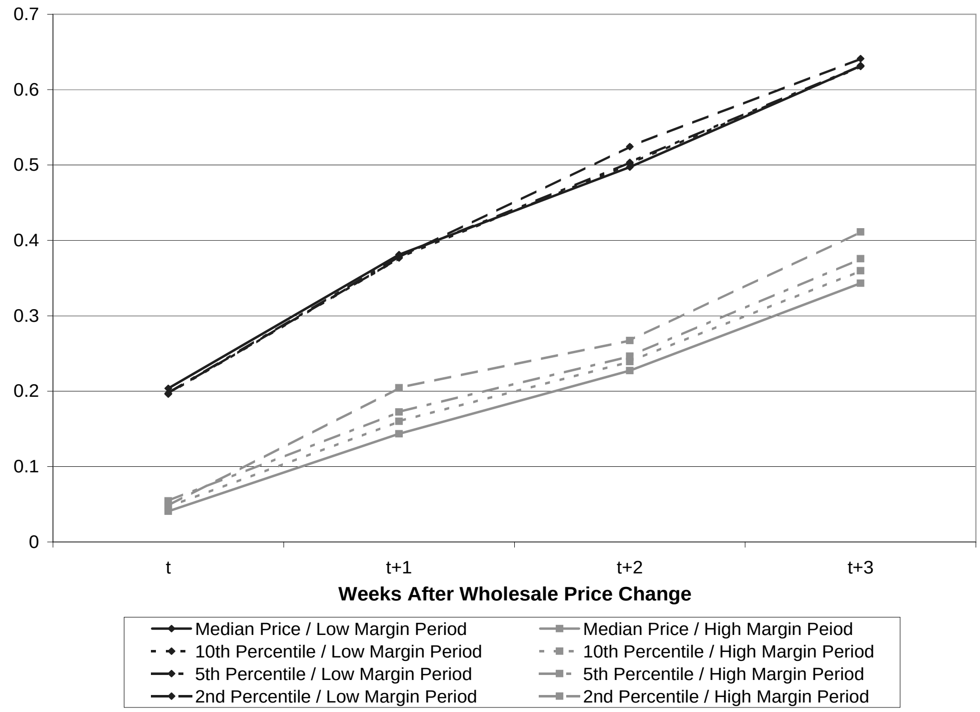
Table 2: Percentile Price Response Regressions

Dependant Variable (cents/gallon)	Median Price	10th Percentile Price	5th Percentile Price	2nd Percentile Price
Δc^{lm}_{t}	$.204^{**}$	$.196^{**}$	$.197^{**}$	$.197^{**}$
	$(.053)$	$(.051)$	$(.050)$	$(.050)$
Δc^{lm}_{t-1}	$.040$	$.046$	$.050$	$.061$
	$(.061)$	$(.059)$	$(.058)$	$(.059)$
Δc^{lm}_{t-2}	$-.008$	$-.006$	$-.008$	$.008$
	$(.054)$	$(.051)$	$(.050)$	$(.049)$
Δc^{lm}_{t-3}	$.040$	$.028$	$.025$	$.003$
	$(.047)$	$(.043)$	$(.042)$	$(.043)$
Δp^{lm}_{t-1}	$.270^{*}$	$.271^{*}$	$.249$	$.166$
	$(.152)$	$(.161)$	$(.157)$	$(.148)$
Δp^{lm}_{t-2}	$.058$	$.095$	$.117$	$.212$
	$(.109)$	$(.108)$	$(.111)$	$(.109)$
Δc^{hm}_{t}	$.041$	$.046$	$.055$	$.048$
	$(.034)$	$(.028)$	$(.037)$	$(.061)$
Δc^{hm}_{t-1}	$.051^{*}$	$.058^{**}$	$.062^{**}$	$.084^{**}$
	$(.030)$	$(.025)$	$(.024)$	$(.042)$
Δc^{hm}_{t-2}	$-.012$	$-.023$	$-.022$	$-.030$
	$(.023)$	$(.029)$	$(.032)$	$(.050)$
Δc^{hm}_{t-3}	$.023$	$.035^{*}$	$.040^{*}$	$.043^{*}$
	$(.020)$	$(.019)$	$(.024)$	$(.040)$
Δp^{hm}_{t-1}	$.636^{**}$	$.656^{**}$	$.473^{**}$	$.169$
	$(.186)$	$(.172)$	$(.144)$	$(.188)$
Δp^{hm}_{t-2}	$.181$	$.115$	$.249^{*}$	$.262$
	$(.174)$	$(.163)$	$(.138)$	$(.163)$
Error Corrction Term^{lm}	$-.027^{**}$	$-.026^{**}$	$-.032^{*}$	$-.067^{**}$
	$(.012)$	$(.012)$	$(.019)$	$(.029)$
Error Corrction Term^{hm}	$-.104^{**}$	$-.101^{**}$	$-.102^{**}$	$-.108^{**}$
	$(.041)$	$(.041)$	$(.043)$	$(.044)$
obs	92	92	92	92
R^2	$.738$	$.751$	$.740$	$.670$

Dependant Variable: Weekly change in the Xth percentile of the retail price distribution

** Denotes significance at the 5% level, * 10% level

Figure 8: Percentile Price Response Function Estimates During High and Low Margin Periods



in the market adjust to cost changes at roughly the same speed as the median station. There are no statistically significant differences across percentiles in the estimated cumulative response functions during either the high or low margin periods. Moreover, all the price percentiles reveal significant asymmetry in their response during high and low margin periods.[41] The difference between estimated response functions in high and low margin periods is only slightly smaller for the lower percentiles than for the median.

The results suggest that all stations appear to pass through cost changes at similar speeds, as they would if they were facing the marketwide demand conditions described in the reference price search model. This does not support the idea that asymmetric adjustment results from stations engaging in focal price collusion. There is no evidence that the stations charging the lowest prices in the city are responding to cost declines more quickly than the typical station, as we would expect if they had broken from collusion earlier.

price response estimated using the seven years of data from Los Angeles. This could indicate a slight difference in behavior across cities, or it may be consequence of the relative difficulty of estimating price response from a fairly short two year period. Nevertheless, the general patterns of response are similar to those from the Los Angeles data, and the response estimates across different specifications using the two year sample are fairly consistent.

[41]For each percentile, the cumulative difference between the response during high and low margin periods is statistically significant at the 5% level.

5.3 Changes in Price Dispersion

As a final test of the predictions of the reference price search model, I examine how the extent of price dispersion changes as the overall price level fluctuates. The equilibrium price distributions of the reference price search model displayed in Figure 2 show that price dispersion generally increases as margins increase (or, alternatively, as retail prices fall relative to expectations). When retail prices fall (or are lower than expected), fewer consumers choose to search. Therefore, more consumers are likely to buy at higher priced stations, and both price dispersion and margins increase. This simple prediction can be tested by empirically examining how dispersion in station prices from San Diego changes over time in relation to profit margins.

I consider two different measures of price dispersion: a localized measure and a citywide measure. The local price dispersion around a station in a given week is measured using the standard deviation of the prices of competing stations within one half mile. The citywide measure considers the standard deviation of prices for all stations. To control for station heterogeneity, I once again use the distribution of adjusted prices which contains station prices net of the station's average price premium over the sample period. I also want to control for temporary price differences between stations that can occur during market wide price movements simply because some stations may move their prices slightly earlier than others. Larger overall price movements will create more of this temporary dispersion. Therefore, I estimate a simple regression of price dispersion as a function of the lagged margin as well as the current change in the retail price. In the local dispersion regression these are measured by the average margin of stations within one half mile and the change in the average prices of these stations. A Prais-Winsten estimation procedure is used to control for serial correlation in the errors. Separate coefficients for positive and negative changes in retail price are included to allow for these changes to have different effects on price dispersion. Table 3, column 1 shows the coefficient estimates the local dispersion regression including robust standard errors that allow for possible correlation across stations within a given week. The results for the city dispersion model are reported in column 2. This is a regression of the city-wide standard deviation of station prices in each week on the city-average margin and retail price change.

The coefficients on margin are positive and highly significant in both regressions. Controlling for recent price movements, the standard deviation of local prices tends to be .54 cents/gallon (or roughly 21%) higher in periods when the margin is one standard deviation above the mean

Table 3: Station Price Dispersion Regressions

Dependant Variable (cents/gallon)	S.D. of stations within one half mile	city-wide S.D.
Margin_{t-1}	$.0161^{***}$	$.0143^{*}$
	$(.0059)$	$(.0076)$
Δp_t^+	$.1449^{***}$	$.2008^{***}$
	$(.0209)$	$(.0250)$
Δp_t^-	$.0424$	$-.0361$
	$(.0273)$	$(.0665)$
constant	2.125^{***}	3.041^{***}
	$(.1795)$	$(.1955)$
Dependant Variable:		
$\text{Mean}(SD_t)$	2.543	3.600
$\text{s.d.}(SD_t)$	2.314	.972
obs	25021	92

Robust-Clustered standard errors are presented
** Denotes significance at the 5% level, * 10% level
Station fixed effects included in station level regression

than when the local average margin is one standard deviation below the mean. The citywide model implies that the standard deviation of all prices in the market tends to be .46 cents/gallon (or roughly 13%) higher when the city average margin is one standard deviation above the mean compared to when it is one standard deviation below. This positive relationship between dispersion and margins is consistent with the basic prediction of the reference price search equilibrium.

The coefficient on current positive price change is also positive and strongly significant. This suggests that large temporary price differences between stations do arise during periods of rapid price adjustment. Positive price changes appear to have a larger impact on dispersion than negative changes. This may be because positive price movements by stations are often larger (resulting from a sudden positive cost shock) whereas negative price changes are usually small and gradual. This source of price dispersion is not incorporated in the reference price search model. However, the significance of the current positive price change in the regression illustrates the importance of empirically controlling for recent price movements when estimating the relationship between margins and dispersion.

While the positive relationship between margins and dispersion is generally supported by the reference price search model, the increase in localized price dispersion during high margin periods is somewhat at odds with the focal price collusion explanation. If localized groups of stations were colluding to keep margins high, one would expect less dispersion amongst these competitors during high margin periods. This contradicts the findings reported in Table 3.

6 Conclusion

The reference price search model presented in this paper provides a new explanation for why prices rise faster than they fall in response to cost changes. The predictions of this model differ in important ways from those of previously suggested theories of asymmetric price response, and I empirically show that the model's predictions match observed retail gasoline pricing patterns better than those of the previous theories.

Following the predictions of the reference price search model, I show that prices respond faster to cost changes during periods when margins are low.[42] This fact has not been previously established in the empirical literature, and it is inconsistent with other consumer search models that have been proposed to explain asymmetric price adjustment. Using station level price data I also show that even the lowest prices in the market adjust asymmetrically, and that dispersion in prices even amongst local competitors increases during periods of high margins. These patterns are consistent with the reference price search model but are not well explained by collusive models of asymmetric adjustment. Together the evidence suggests that consumers' imperfect knowledge of current price levels may have a significant influence on prices in retail gasoline markets.

The reference price search model also highlights an important inefficiency in this market. Incorrect consumer expectations can lead to periods in which prices are well above their full information competitive level. If all consumers were searching and were informed about the prices in the market, the reduction in equilibrium prices would be much larger than the sum of consumers' search costs. However, given that consumers have limited information, all firms charge higher prices and an individual consumer cannot significantly gain by searching to acquire price information. The data reveal the presence of this inefficiency. Even when retail prices are well above wholesale costs, there is relatively little variation in prices across stations. Therefore, one consumer would not gain much by choosing to search, even though firms would significantly lower their prices if all consumers were searching.

The basic theoretical insights and empirical contributions of this paper should help further the understanding of asymmetric price adjustment in other markets as well. While the reference price search model was motivated by search behavior in the gasoline market, it is general enough to apply to other goods with similar consumer search characteristics. More importantly, the em-

[42]This sentence corrects a typographical error appearing in the published version.

pirical tests used to compare predictions of the theoretical models to observed behavior can also be used to help identify the causes of asymmetric adjustment in other markets.

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Figure 9: Weekly Los Angeles Average Gasoline Prices: 2000-2007

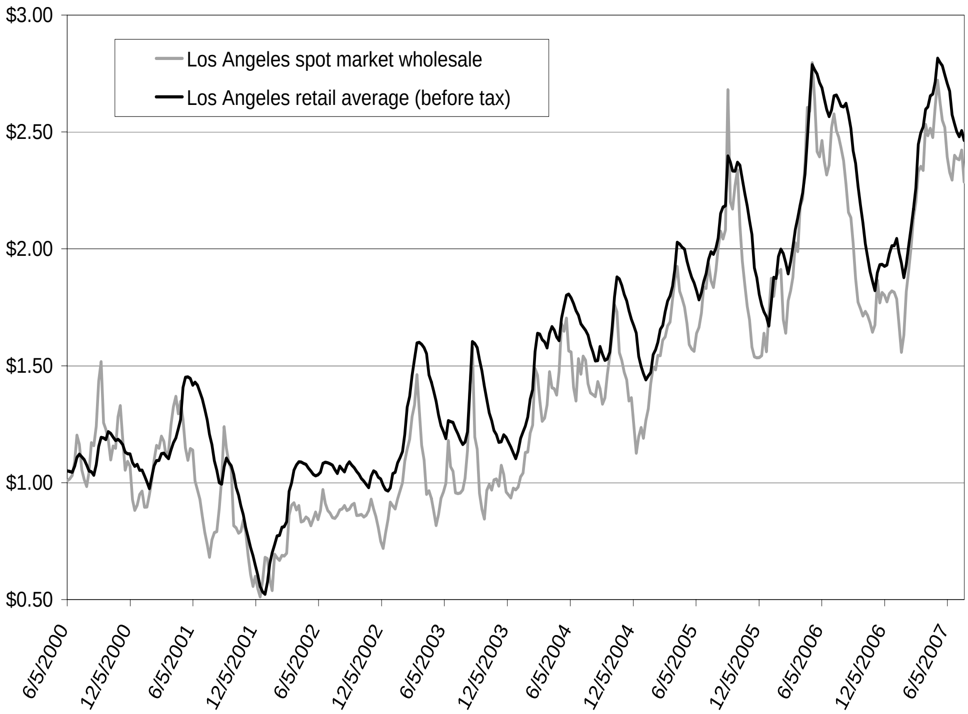
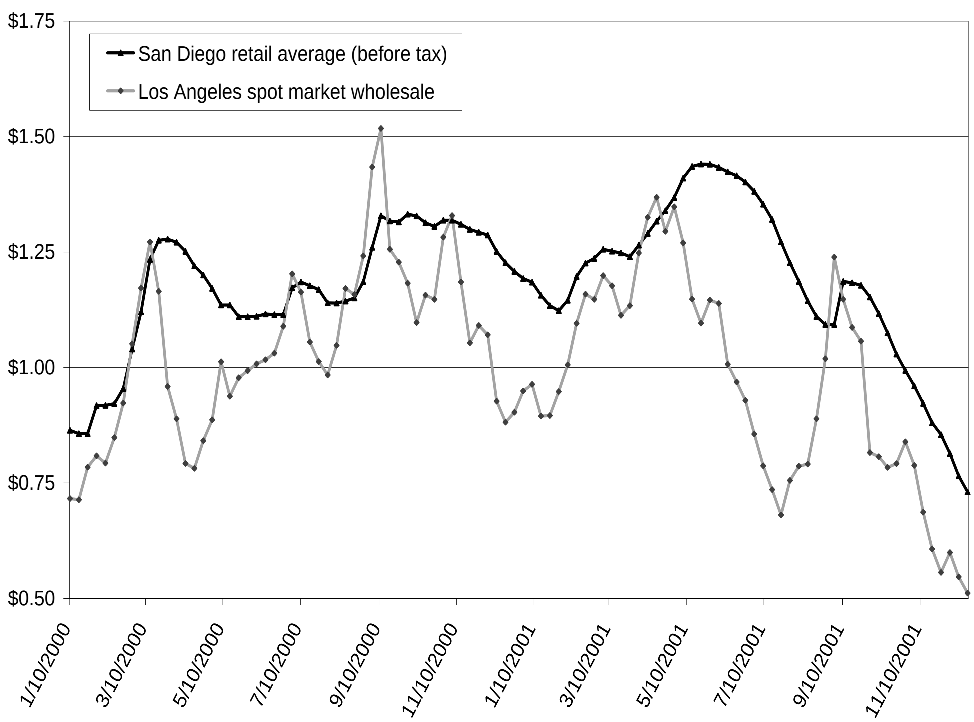


Figure 10: Weekly San Diego Average Gasoline Prices: 2000-2001



Notes: Los Angeles retail is an average of prices from a sample of stations observed every Monday by the US Department of Energy. LA Spot prices are average of daily spot market prices from the previous week. The San Diego retail is an average of prices from a sample of stations observed every Monday by the Utility Consumer Action Network.

Appendix A: Proofs

Lemma 1 *$\Pi^{ns}(p)$ is uniquely maximized at $\text{argmax}_p \Pi^{ns}(p) = \tilde{p}$ such that $\tilde{p} = \phi(\tilde{p}) + c$ and $\max_p \Pi^{ns}(p) = \frac{N}{2}(\tilde{p} - c)^2 S'(\tilde{p}) = \left(\frac{N}{2}\right) \frac{(1-S(\tilde{p}))^2}{S'(\tilde{p})}$.*

Proof: $\tilde{p} = \text{argmax}_p \Pi^{ns}(p)$ satisfies:

$$\frac{\mathrm{d}\Pi_1^{ns}}{\mathrm{d}p_1}(\tilde{p}) = \frac{N}{2}\left[-(\tilde{p} - c)S'(\tilde{p}) + (1 - S(\tilde{p}))\right] = 0$$

or more simply: $\tilde{p} = \phi(\tilde{p}) + c$. This solution is unique since $p - \phi(p)$ is a strictly increasing function (due to the monotone hazard rate assumption), and can only equal c at one value of p. The corresponding level of profit is:

$$\max_p \Pi^{ns}(p) = \frac{N}{2}(\tilde{p} - c)(1 - S(\tilde{p})) = \frac{N}{2}(\tilde{p} - c)^2 S'(\tilde{p}) = \left(\frac{N}{2}\right) \frac{(1 - S(\tilde{p}))^2}{S'(\tilde{p})}. \qquad \blacksquare$$

Proposition 1

1. *As long as there are some non-searching consumers (ie. $S(p) < 1$) no pure strategy equilibrium will exist.*

2. *The mixed strategy equilibrium F(p) over support $[\underline{p}, \overline{p}]$ has the following properties:*

   (a) *$\underline{p} = \tilde{p}$ where $\tilde{p} = \phi(\tilde{p}) + c$*

   (b) *Expected profit $\Pi^* = \frac{N}{2}(\tilde{p} - c)(1 - S(\tilde{p}))$.*

   (c) *$\underline{p}$ satisfies the following (for Firm 1):*

$$(\underline{p}_1 - c)\left[1 + \int_{\underline{p}_1}^{\overline{p}} S(p_2) f(p_2) \mathrm{d}p_2\right] = (\tilde{p} - c)(1 - S(\tilde{p}))$$

Proof: Part 1: Suppose $p_1 = p_2 > c$. When $S(p) < 1$ there exists an ϵ such that $c < p_1 - \epsilon < p_1$, where

$$\Pi(p_1 - \epsilon) = \Pi^{ns}(p_1 - \epsilon) + \Pi^s(p_1 - \epsilon) > \Pi^{ns}(p_1) + \frac{1}{2}\Pi^s(p_1) = \Pi(p_1).$$

Therefore $p_1 = p_2$ is not a best response to p_2.

Suppose $p_1 < p_2$. Then there exists a p^* such that $p_1 < p^* < p_2$. It is immediate that $x_1(p^*) = x_1(p_1)$ and, therefore, $\Pi_1(p^*) > \Pi(p_1)$. So $p_1 < p_2$ is not a best response to p_2.

Suppose $p_1 = p_2 = c$. When $S(p) < 1$ there exists some $p^* > p_1 = c$ such that $\Pi_1(p^*) = \Pi_1^{ns}(p^*) > \Pi(p_1) = 0$. So $p_1 = c$ is not a best response to $p_2 = c$. Hence, there is no pure strategy equilibrium when $S(p) < 1$.

Part 2(a): Any price charged in equilibrium must have expected profit at least as large as the profit from $p = \tilde{p}$ because the firm can earn $\Pi(\tilde{p})$ regardless of the strategy played by the other firm. With out loss of generality, assume there is an equilibrium pair of mixed strategies for the firms such that $\overline{p_1} \geq \overline{p_2} > \tilde{p}$. Firm 1 makes some positive profit by selling to it's non-searching consumers. However, $\Pi(\overline{p_1}) < \Pi(\tilde{p})$ since $\overline{p_1} \neq \tilde{p} = argmax \Pi^{ns}(p)$. This implies an expected profit $\Pi p < \Pi(\tilde{p})$ which can not be an equilibrium. Now assume there is an equilibrium pair of mixed strategies such that $\overline{p_2} \leq \overline{p_1} < \tilde{p}$. For $p_1 \geq \overline{p}_2$ no searching consumers purchase from Firm 1. In this range of p_1, $\Pi_1(p_1) = \Pi^{ns}(p_1)$. For any $p_1 < \tilde{p}$, $\Pi_1(p_1)$ is less than $\Pi(\tilde{p})$ which can not be true in equilibrium. Therefore, equilibrium strategies must satisfy $\overline{p}_1 = \overline{p}_2 = \tilde{p}$.

Part 2(b): Since Part 1 concludes that $\tilde{p}$ is in the support of an equilibrium mixed strategy, all values of p in the support must have expected profit equal to $\Pi(\tilde{p}) = \frac{N}{2}(\tilde{p} - c)(1 - S(\tilde{p}))$.

Part 2(c): In an equilibrium with $\underline{p}_1 = \underline{p}_2 = \underline{p}$, expected profit for Firm 1 at $p_1 = \underline{p}$ is

$$\Pi_1(\underline{p}) = \frac{N}{2}(\underline{p} - c)\left[1 + \int_{\underline{p}}^{\overline{p}} S(p_2) f(p_2) \mathrm{d}p_2\right].$$

Part (b) concludes that $\Pi(\underline{p}) = \Pi^*$. Therefore, $\underline{p}$ is implicitly defined by:

$$(\underline{p} - c)\left[1 + \int_{\underline{p}}^{\overline{p}} S(p_2) f(p_2) \mathrm{d}p_2\right] = (\tilde{p} - c)(1 - S(\tilde{p})). \quad \blacksquare$$