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Search, Price Dispersion, and Local Competition: Estimating Heterogeneous Search Costs in Retail Gasoline Markets

by

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Abstract

Information frictions play a key role in a wide array of economic environments and are frequently incorporated into formal models as search costs. Yet, as search costs are typically unobserved, little empirical work investigates the determinants of the distribution of consumer search costs and the implications for policy. This paper explores the sources of heterogeneity in consumer search costs and how this heterogeneity and market structure shape firms' equilibrium pricing and consumers' search behavior in retail gasoline markets. We estimate the distribution of consumer search costs using price data for a large number of geographically isolated markets across the United States. The results demonstrate that the distribution of consumer search costs varies significantly across geographic markets and that market and population characteristics, such as household income, explain some of the variation. Policy counterfactuals suggest that the shape of the consumer search cost distribution has important implications for both government policy and firms' strategic pricing behavior. The experiments reveal that (1) the search cost distribution needs to be sufficiently heterogeneous to generate equilibrium price dispersion, and (2) the market-level expected price paid decreases in the number of firms, but consumers with high search costs may be worse off from an increased number of firms.

1 Introduction

Information frictions play a key role in explaining many aspects of economic activity. For instance, a robust body of economic research has identified and explained the existence of price dispersion in both homogeneous and differentiated product markets as a consequence of consumer search costs. Since Stigler's (1961) seminal article, a number of influential theoretical papers, such as Varian (1980), Burdett and Judd (1983), and Stahl (1989), demonstrate that information frictions resulting from consumer search costs can lead to competing firms setting different prices for homogeneous goods.[1] Search costs have also played an important role in characterizing labor and monetary markets.[2]

Although search costs are an important component of many theoretical models, we know very little about what determines consumers' search cost distributions and its implications for policy and pricing as search costs are typically unobserved. For instance, there exists little empirical work that documents how and why consumer search costs vary across geographic markets. This gap in the literature is unfortunate because measuring and understanding the source of variation in search costs can benefit government policy and help understand firms' pricing strategy, which critically depends upon both market structure and the distribution of consumer search costs in a market. For instance, as we later show, a policy or technological improvement that lowers the average cost of search, but also reduces the variance of the search cost distribution, can lead to higher equilibrium prices.

This paper fills this gap by exploring the determinants of consumer search costs and their role in shaping equilibrium pricing and search behavior. To do so, we first structurally estimate the search cost distributions for each of many retail gasoline geographic markets. We document that search costs vary considerably both within and across markets. As detailed below, the shape of the consumer search cost distribution has important implications for both government policy and firms' strategic pricing behavior. In our counterfactual policy experiments, we find that (1) the search cost distribution needs to be sufficiently heterogeneous to generate equilibrium price dispersion, and (2) the market-level expected price paid decreases in the number of firms, but consumers with high search costs may be worse off from an increased number of firms.[3]

[1] See Baye, Morgan, and Scholten (2006) for a broad review of the consumer search and price dispersion literature.

[2] For reviews of search-theoretic models in labor economics, see Rogerson, Shimer, and Wright (2005) and Eckstein and Van den Berg (2007). For reviews in monetary economics, see Rupert, Schindler, Shevchenko, and Wright (2000).

[3] We use the terms "gas station" and "firm" interchangeably.

We proceed in two steps. First, the extent to which consumers' search costs vary across geographic markets is explored. Instead of relying on indirect measures of search behavior, such as internet usage for searching for online insurance products (Brown and Goolsbee 2002), we leverage the non-sequential search model developed in Burdett and Judd (1983) to directly recover the consumer search cost distribution that rationalizes observed gasoline prices as an equilibrium outcome generated by gas stations pricing to consumers with heterogenous search costs (Hong and Shum 2006; Moraga-González and Wildenbeest 2008; Wildenbeest 2011). To obtain multiple cross-sectional observations, which we need to examine the heterogeneity of search costs across markets, we define geographically isolated markets in the spirit of Bresnahan and Reiss (1991). Facilitated by daily gasoline prices for many geographically diverse local markets in the United States, we estimate the distribution of search costs for each of these markets. We establish that both the mean and variance of the search cost distributions vary considerably across geographic markets. By relating the variation in the distribution of search costs across markets to variation in market characteristics, we find that the search cost distribution is closely related to the distribution of household income; markets with a higher earning population are characterized by higher search costs. Furthermore, markets with more dispersed household income have more dispersed search costs. These results suggest that consumers' search costs are, in part, driven by opportunity costs. Meanwhile, we do not find a relationship between search costs and other potentially informative population characteristics such as the age, education, and the mean distance among stations.

Second, using the estimated structural parameters, we conduct policy experiments to investigate the effect of heterogeneity in consumer search costs on equilibrium prices and consumer welfare. We run two experiments, which suggest that the shape of the consumer search cost distribution has important implications for both government policy and firms' strategic pricing behavior. The first experiment studies how two exogenous changes in the search cost distribution, in the sense of first-order stochastic dominance and second-order stochastic dominance, respectively, changes price equilibria. As Armstrong (2008) notes, competition policy affecting consumer search costs has an ambiguous affect on the price paid by "searchers" and "non-searchers". We find that a decrease in search costs such that the new search cost distribution is first-order stochastically dominated by the original distribution leads to a decrease in the expected price paid for all consumers; however, the paid search costs decrease only for people with low search costs, whereas the paid search costs increase for people with median search costs. The total expenditure decreases for nearly all consumers, and the benefit is larger for consumers with smaller search costs. For the second-order stochastically dominant change, we confirm that heterogeneity and not the level of expected search costs is the key to generating equilibrium price dispersion. We find that making search costs more homogeneous such that the new search costs distribution second-order stochastically dominate the original distribution may lead to higher total expenditure in terms of prices and paid search costs. If the distribution of search costs become sufficiently homogeneous (although the distribution need not be degenerate), all firms set the monopoly price. Overall, our findings highlight that competition policy should incorporate search cost distributions to fully capture the effect on prices and consumer surplus.

The second experiment analyzes how an increase in the number of firms affects the equilibrium price distribution. Not surprisingly, we find that the minimum market price decreases in the number of gas stations. More interestingly, the experiment illustrates that increasing the number of stations in a market initially decreases the expected price, but as the number of firms increases beyond four the expected price increases, which stands in contrast to the predictions of the standard Cournot and differentiated Bertrand models. Expected price paid, on the other hand, declines as the number of gas stations increases and attains its minimum at 13 stations.[4] We also confirm a non-monotonic relationship between one measure of price dispersion and the number of firms; the standard deviation of prices has an inverse u-shape and attains its maximum in a market with around 18 stations. Finally, we observe that a change in market structure differentially impacts people with different search costs. For example, when the number of stations increases from five to six, consumers in the 10th percentile of the search cost distribution decrease their total expenditures, whereas consumers in 75th percentile increase total expenditures.

This paper is a continuation of a recent strand of research in industrial organization that uses structural assumptions to estimate consumer search costs from price data. Hortaçsu and Syverson (2004) use data on S&P 500 index funds to estimate search costs; the econometric framework in that article allows for horizontal product differentiation but requires both price and quantity data - the latter of which is often difficult to obtain. Hong and Shum (2006) are the first to demonstrate how, in homogeneous goods markets, firms' profit-maximizing conditions can be used as moment restrictions in an empirical likelihood estimation routine to back-out the consumer

[4]The expected market price is the expected value of the price cumulative distribution function (i.e. the expected price from a random draw in a given market. The expected price paid, on the other hand, is the expected minimum price among a consumer's set of price quotes. In other words, the price paid factors in what the consumer expects to actually pay, which depends upon the consumer's cost of search and the number of searches. See Section 4 for the formal definition of the expected price paid.

search cost distribution from only price data. Moraga-González and Wildenbeest (2008) extend Hong and Shum (2006) through the maximum likelihood estimation approach and achieve more favorable convergence properties. Wildenbeest (2011) builds on Hong and Shum (2006) to include vertical product differentiation to estimate the distribution of search costs using price data from four grocery stores in the UK. Using the methods developed in Hong and Shum (2006), Moraga-González and Wildenbeest (2008), and Wildenbeest (2011), we estimate the parameters of the search cost distribution that justify the observed regular gasoline price distributions. Unlike such previous research that estimates consumer search costs for a single market, however, this paper uncovers the distribution of consumer search costs for 354 local markets to investigate the heterogeneity of search costs across markets. This paper is related to a recent study by Moraga-González, Sándor, and Wildenbeest (2013b), which use price observations from multiple markets to achieve, via semi-nonparametric estimation, a more precise search cost distribution that is common to all product markets. Our paper, by contrast, estimates the search costs market by market to document the heterogeneity of search costs across geographical markets.

This paper is related to the literature on price dispersion and consumer search in the retail gasoline market. A number of studies, such as Marvel (1976), Lewis (2008), Chandra and Tappata (2011), Pennerstorfer, Schmidt-Dengler, Schutz, Weiss, and Yontcheva (2014) have identified patterns of temporal and cross-sectional price dispersion in retail gasoline markets that are consistent with models of costly consumer search.[5] The reduced-form approach of studying the relationship between price dispersion and market characteristics is also conducted in other product markets.[6] Although the analysis in these studies is carefully executed, because search costs are not directly observed, the evidence has been limited to reduced-form testing of the comparative static relationships implied by a particular theoretical model. By contrast, by directly estimating the search cost distributions that rationalize the data, we push the literature forward by quantifying the effect consumer search cost heterogeneity has on changes in market structure and policies that effect

[5] For example, using a superset of the data used in this study, Chandra and Tappata (2011) find that the price ranking of firms varies less for more closely located firms and that price dispersion increases in the number of firms in a market. Lewis (2008) uses weekly price data for stations in the San Diego area and similarly finds that patterns of price dispersion are consistent with a model of consumer search. Lewis and Marvel (2011) use website traffic data for gasoline price comparison sites to characterize the patterns of consumer search on the internet. Barron, Taylor, and Umbeck (2004) use a large cross-section of station-level price data in four large US cities and find patterns of price dispersion consistent with some models of consumer search. More broadly, this paper is also related to several studies on price dispersion in the retail gasoline markets. See, for example, Hosken, McMillan, and Taylor (2008), and Lach and Moraga-González (2012). For recent empirical work on retail gasoline markets, see Eckert (2013) and references therein.

[6] See, for example, Baye, Morgan, and Scholten, 1994 (consumer electronics), Sorensen, 2000 (prescription drugs), Lach, 2002 (grocery stores), Brown and Goolsbee, 2002 (life insurance), and Vukina and Zheng, 2010 (live hog).

consumer search.

Finally, this paper is related to the extensive literature, both theoretical and empirical, on how market structure affects the equilibrium price distribution in the presence of market frictions and consumer search (Rosenthal 1980; Varian 1980; Stiglitz 1987; Stahl 1994; Janssen and Moraga-González 2004; Moraga-González, Sándor, Wildenbeest 2010 and 2013a; Lach and Moraga-González 2012). Our work differs from those papers in that we employ the estimated structural parameters of the model to quantify the effects of changes in market structure on the prices and paid search costs for consumers with different levels of search costs.

Our paper proceeds as follows. Section 2 describes the data, how we choose markets within which to perform the estimation, and reduced-form analysis on price dispersion. Section 3 details the empirical model and estimation results. Section 4 conducts the counterfactual experiments. Section 5 concludes.

2 The Data

2.1 Price Data

The analysis in this paper benefits from a large panel data set of daily gasoline prices. The data originate from the Oil Price Information Service (OPIS), which obtains data either directly from gas stations or indirectly from credit card transactions.[7] OPIS's data have frequently been relied upon in academic studies of the retail gasoline industry (e.g. Lewis and Noel 2011; Taylor, Kreisle, and Zimmerman 2010; and Chandra and Tappata 2011).

The data cover daily station prices from January 4th, 2006 through May 16th, 2007 for stations in California, Florida, New Jersey, and Texas, which amounts to more than $20,000$ stations. This data set was previously utilized in Chandra and Tappata (2011).[8]

2.2 Location Data and Selecting Isolated Markets

In the retail gasoline markets, competition among stations is highly localized (Eckert 2013). The location of firms plays an important role in our analysis, both in the selection of markets within which to estimate search costs and in constructing control variables for subsequent regressions.

[7] OPIS's website states that their data originates from "exclusive relationships with credit card companies, direct feeds, and other survey methods."

[8] We refer interested readers to Chandra and Tappata (2011) for a more detailed data description.

To pinpoint the geographic location of each firm, street addresses were converted to longitude and latitude coordinates using ArcGIS and then cross-referenced with coordinates outputted from Yahoo maps.

In the structural model, prices are generated by an equilibrium in which a defined set of gas stations all compete against each other for the same set of customers. Markets in the data must be carefully defined to be consistent with this assumption. Typically, the literature on retail gasoline markets defines each firm in the data to be at the center of a market of a specified radius.[9] A potential difficulty and source of estimation bias inherent in this market definition is overlapping markets; two firms within a specified distance that compete against each other may not share the same set of total competitors.[10]

To circumvent this problem, the analysis focuses on what we define to be "isolated" markets in the spirit of Bresnahan and Reiss's (1991) geographic market definition. We use two strict criteria. First, let J be a set of firms and let $d(i, j)$ be the Euclidean distance between any two firms $i, j \in J$. Then, J is an isolated market if for all $i, j \in J$, $d(i, j) \leq X$, and for all $k \notin J$ and $i \in J$ $d(i, k) > X$. For the analysis presented below, X is set be 1.5 miles; thus an isolated market is a set of firms all within 1.5 mile of each other and no other competitor is within 1.5 mile of any firm in the market. The maximum distance between firms in a market is chosen to be 1.5 miles, which is consistent with previous studies such as Barron, Taylor, and Umbeck (2004), Hosken, McMillan, and Taylor (2008), and Lewis (2008). This market definition ensures that the observed prices in a market are not influenced by competition with unobserved competitors.

To analyze the relationship between search costs and census tract level characteristics, isolated markets are further restricted to only include markets where all gas stations are located within a single census tract. Figure 1 depicts a map that contains such an isolated markets with multiple firms and a single census tract ("Market 1"). Using this market definition, we estimate the model using $11,736$ price observations from $1,127$ stations in 354 isolated (and single census tract) markets. Figure 2 shows the distribution of those markets by market structure. Although our market definition still contains some potential issues, such as people may purchase gasoline not only where they live, but also where they commute for work, the requirements for the market definition in this

[9] For example, see Hastings (2004), Barron, Taylor, and Umbeck (2004), Lewis (2008), and Remer (2013).

[10] For example, suppose three firms, A, B, and C, are located one mile apart in sequence along a road. Using a cutoff distance of 1.5 miles for the radius, we obtain three markets, A and B, A, B, and C, and B and C. It would, however, be inappropriate to treat market outcomes from these three markets as three independent observations to draw inferences on each of those markets because firm A and C's pricing is dependent through firm B's pricing.

study are more stringent than those used by most of the existing literature.[11]

2.3 Cost data

The structural model that we estimate requires only price data, and reconciles the observed price dispersion as a consequence of vertical product differentiation and heterogeneity in consumers' cost of search. In our data, however, prices may vary over time in response to changes in the wholesale cost of gasoline. To minimize the effect of marginal cost changes on the observed price dispersion, the model is estimated using the 30 day window in the data where the variation in wholesale price of gasoline is minimized. As the price at which each retailer purchased their product is privately negotiated and unavailable, we utilize the price of wholesale gasoline traded on the New York Mercantile Exchange (NYMEX), which is likely to be highly correlated with actual marginal costs. These data are commonly employed as a measure of marginal cost in studies of the retail gasoline industry.[12] We estimate the model using price data from March 3rd through April 1st, 2006, where the standard deviation of the daily price of wholesale unleaded fuel shipped from the NY Harbor was 6.3 cents per gallon.[13]

2.4 Descriptive Evidence of Price Dispersion

Both survey evidence and the economic literature demonstrate that consumer search plays an important role in the retail gasoline industry. The National Association for Convenience and Fuel Retailing (NACS) has been surveying gasoline consumers since 2007 and has consistently found that price is overwhelmingly the most important factor in buying gasoline.[14] They also find that about 68% of people would drive five minutes out of their way to save 5 cents per gallon, but only 36% of people would drive ten minutes to save the same amount. Similar results throughout the survey suggest that (i) a large fraction of people search to save money on gasoline expenditures and (ii) the intensity with which customers search varies.

We run OLS regressions to document the relationship between measures of price dispersion and market characteristics. The census-level data used as explanatory variables is taken from the

[11] A notable exception is Houde (2012), who focuses on the Quebec City gasoline market and takes commuting routes into account.

[12] See, for example, Borenstein, Cameron, and Gilbert (1997), Velinda (2008), and Lewis (2011).

[13] Note also that there are brief windows in the data set where price data are missing. These days were a priori excluded as potential times over which to perform the estimation.

[14] See http://www.nacsonline.com/YourBusiness/FuelsReports/GasPrices_2013/Pages/Consumers-React-to-Gas-Prices.aspx.

2006-2010 American Community Survey (ACS), which is an ongoing survey conducted under the auspices of the US Census Bureau. Mean income and age are taken directly from the survey, while mean years of education are calculated by taking a weighted average of the proportion of people in a census tract who have reached a particular educational attainment. For each census tract, the ACS reports the number of households that fall within a particular income bracket; by assuming that average household income within a bracket is the mid-point of the bracket, we calculate the standard deviation of income. The mean distance between stations in a market is constructed by measuring the mean Euclidean distance between all stations in a market. Table A1 in Appendix presents basic summary statistics of the variables from ACS for 354 single-census isolated markets in our data.

Table 1 documents general price statistics for 354 isolated markets. As the number of stations increases the sample range monotonically increases, whereas there is no uniform relationship between the the sample standard deviation and the number of firms. This pattern suggests that different measures of price dispersion correlate differently with market structure, which may limit the ability of reduced-form analysis to infer the link between price dispersion and search costs.

Table A2 in Appendix shows the results of regressing two measures of price dispersion on the market characteristic variables. We define sample range as the difference between the maximum and minimum price for a given market. We find a robust relationship between price dispersion and some market characteristics, such as income and the number of firms in a market, but not all results are robust to how price dispersion is measured. For example, mean household income is always positively and significantly correlated with price dispersion with at least 95% confidence. On the other hand, the standard deviation of household income has a significant negative relationship with price dispersion (at the 90% confidence level) only when specified in logs, and otherwise has no significant link. Consistent with Table 1, the number of firms in the market has a positive and significant relationship with the market price range, but is not found to have any relationship with the standard deviation of prices. This result highlights a benefit of using a structural model to study the relationship between price dispersion and search costs; the relationship can be directly estimated and is not tied to a particular measure of price dispersion.

3 Model Estimation

3.1 Empirical Model of Search and Price Equilibrium

This subsection introduces a non-sequential search model based on Burdett and Judd (1983) and explains how the model can be used to estimate the distribution of consumer search costs.[15] Our model presentation borrows from Hong and Shum (2006) and Moraga-González and Wildenbeest (2008).

We first consider a set of gas stations selling a homogeneous product to a continuum of consumers that are identical except for their search costs that are unobservable to the firm.[16] Firms, however, do know the distribution of consumer search costs. Each firm in the market simultaneously chooses its price, p; the cumulative equilibrium price distribution is denoted as F_p, where $\underline{p}$ and $\bar{p}$ are the lower and upper bound, respectively, of the support of F_p. Firms have constant and identical marginal costs of production, denoted as r. In equilibrium, firms play mixed strategies and therefore vary their prices over time.[17][18]

Consumers draw an i.i.d. search cost, $c \geq 0$, from the cumulative search cost distribution, F_c. All consumers have an inelastic demand for a unit of gasoline. Consumers know the distribution of market prices, $F_p(p)$, but they do not know individual firms' prices. Consumers receive one free price quote and must pay a cost, c, for each additional quote. Consumers learn the realization of prices after deciding how many additional quotes to obtain, including no additional quote, which implies the consumer goes with the free quote. With a sample of $l(\geq 1)$ gas prices from l stations, each consumer purchases one unit from the lowest-priced gas station in their sample. A consumer's problem is to minimize the total expected expenditure of purchasing a product by choosing the

[15] We assume that consumers search non-sequentially in retail gasoline markets. See De Los Santos, Hortaçsu, and Wildenbeest (2012) and Honka and Chintagunta (2013) for discussions and empirical testing of these two strategies.

[16] Wildenbeest (2011) demonstrates that specifying the model in terms of utility, rather than price, allows for vertical product differentiation to be incorporated into the model, and controlled for in the estimation by simply adding a fixed-effect. While our empirical model accounts for vertical product differentiation, for expositional purposes in this section, we discuss a homogeneous product market where the price p is the strategic variable. All of the subsequent discussions go through if we replace price with utility.

[17] Several empirical works document that the pricing of retail gasoline stations is consistent with a mixed strategy; see Lewis (2008), Hosken, McMillan and Taylor (2008), Lach and Moraga-González (2009), and Chandra and Tappata (2011).

[18] For expositional simplicity, we present the model by assuming products are homogeneous. Our empirical model extends this framework by assuming that firms play mixed strategies in utilities, which consist of price and quality of a product (Wildenbeest 2011). See the next subsection for details.

number of gas stations to search, $l-1$, where

$$l = \arg\min_{l\geq 1} c\cdot(l-1) + \int_{\underline{p}}^{\bar{p}} l\cdot p(1-F_p(p))^{l-1} f(p)dp.$$

The first term, $c(l-1)$, is the total costs of search.[19] The second term is the expected price paid for the product when a consumer has l quotes from l stations. $(1-F_p(p))^{l-1}$ is the probability that all other stations charge a price higher than p. By searching $i+1$ rather than i stores, a consumer obtains an expected marginal savings, which is denoted as $\Delta_i \equiv Ep_{1:i} - Ep_{1:i+1}$, $i = 1, 2, ...$ Here, $p_{1:i}$ represents the minimum price when a consumer takes i draws from F_p. Accordingly, a consumer with search cost c will sample i stores when $\Delta_{i-1} > c > \Delta_i$. A consumer with $c = \Delta_i$ is indifferent between searching i stores and $i+1$ stores. The proportion of consumers with i price quotes q_i will be $q_1 \equiv 1 - F_c(\Delta_1)$ and $q_i \equiv F_c(\Delta_{i-1}) - F_c(\Delta_i)$ for $i \geq 2$.

Firms maximize profits by choosing a symmetric, mixed-pricing strategy F_p for all $p \in [\underline{p}, \bar{p}]$. Based on the consumer behavior, each firm's total profit can be denoted as $\Pi(p) = (p-r)[\sum_{i=1}^{N} q_i \cdot \frac{i}{N}(1-F_p(p))^{i-1}]$. The firms' profit-maximizing mixed strategies imply a condition that each firm is indifferent between charging the monopoly price $\bar{p}$ and any other price $p \in [\underline{p}, \bar{p}]$, namely

$$\frac{(\bar{p}-r)\tilde{q}_1}{N} = (p-r)[\sum_{i=1}^{N} \tilde{q}_i \cdot \frac{i}{N}(1-F_p(p))^{i-1}], \tag{1}$$

where r is the common marginal cost of selling gasoline for each gas station. In words, firms face a trade-off between setting a high price and selling to less informed customers or setting a low price and capturing more informed customers. In equilibrium, firms are indifferent between all points in the price distribution and therefore maximize profits by playing a mixed strategy over the price distribution. Solving equation (1) for price allows us to represent price as the inverse function

$$p(z) = \frac{\tilde{q}_1(\bar{p}-r)}{\sum_{i=1}^{N} iq_i(1-z)^{i-1}} + r, \tag{2}$$

where $z = F_p(p)$.

[19] We subtract 1 because the first quote is free.

3.2 First Stage: Nonparametric Estimation of Search Cost at the Market Level

Our first stage estimation strategy is based on Hong and Shum (2006) and the extensions developed in Moraga-González and Wildenbeest (2008) and Wildenbeest (2011). The Hong and Shum (2006) framework allows the distribution of consumer search costs to be recovered using price data alone by rationalizing the observed price dispersion as a consequence of search costs. We apply this methodology to each geographically isolated retail gasoline market to document the heterogeneity of search costs across markets.

To identify the model parameters, we use the equilibrium condition specified in equation (1), that in a mixed strategy equilibrium, expected profits are the same for all prices in the support of the equilibrium price distribution. We conduct nonparametric estimation using this optimality condition.

We conduct the maximum likelihood technique developed by Moraga-González and Wildenbeest (2008). Denoting the number of gas stations in a market by N and the number of price observations in that market by M, we employ the MLE estimation strategy to obtain the estimated model parameter $\hat{\theta}_{MLE} = \{\hat{q}_i\}_{i=1}^{N-1}$ such that:

$$\hat{\theta}_{MLE} = \arg \max_{\{q_i\}_{i=1}^{N-1}} \sum_{l=2}^{M-1} \log f_p(p_l; q_1, .., q_N),$$

where f_p is the density for F_p and $F_p(p_l)$ solves equation (1).[20] The maximum likelihood routine yields estimates of a non-parametric search cost CDF represented by a combination of points $\{q_i, \Delta_i\}$.

Finally, we control for potential vertical differentiation by gas stations within a market using Wildenbeest (2011). This method extends Hong and Shum (2006) such that firms play mixed strategies in consumer utility, where $u_j = \delta_j - p_j$ and δ_j is the value consumers realize from purchasing one unit of the good from station j. To implement this model, we parameterize the price at firm j at time t, p_{jt}, as

$$p_{jt} = \alpha + \delta_j + \epsilon_{jt}, \tag{3}$$

and perform the fixed effects regression specified by equation (3) for a given market to recover $\hat{\delta}_j$.We then construct the utility from station j by setting $\hat{u}_{jt} = p_{jt} - \hat{\delta}_j$. By assuming that any

[20] Appendix provides the representation of f_p in F_p, q_i, p, and r.

systematic differences in quality across gas stations are attributed to the differences in prices across those stations, the model reduces to a game in which firms are symmetric in their strategies to randomize its utility.

Estimation results. We estimate the search cost CDF (i.e., a combination of points $\{q_i, \Delta_i\}$) for each of 354 markets. Table 2 presents the statistics that summarize estimated $\hat{F}_c(\hat{\Delta}_i)$, $\hat{\Delta}_i$,and the marginal cost from all those markets. This table demonstrates a large amount of variation in the estimated search costs across markets, as shown in the standard deviation and the range between minimum and maximum of $\hat{q}_1$ and $\hat{\Delta}_1$. To illustrate how estimated search cost distributions vary across markets, we randomly pick five markets that have three stations in Texas. Figure 3a plots $(\Delta_1, F_c(\Delta_1))$ and $(\Delta_2, F_c(\Delta_2))$ for each market.[21] We have Δ_1 and Δ_2 on the horizontal axis and $F_c(\Delta_1)$ and $F_c(\Delta_2)$ on the vertical axis. The figure displays a considerable variation in the distribution across those five markets. For instance, Market 1 has the fraction of nonsearchers $(q_1 = 1 - F_c(\Delta_1))$ as 0.0251, and the gains from search for the first search is \$0.025 $(= \Delta_1)$ per gallon of regular unleaded gasoline. Market 5, on the other hand, has the fraction of nonsearchers as 0.561, and the gains from search for the first search is \$0.056 $(= \Delta_1)$ per gallon.

Because we normalize the minimum price in each market to 1, the price cost margin is on average \$0.267 (= \$1 − \$0.733) per gallon.[22] The equilibrium price distribution from the estimated model approximates the empirical distribution of prices in most markets. For instance, Figure 3b presents the empirical and estimated price distribution from a market in Texas.

In the next subsection, we seek to explain this search cost heterogeneity across markets by using market characteristics.

3.3 Second Stage: Estimation of Parametric Search Cost Distribution that Allows for Variation across Markets

This subsection sheds light on the underlying source of heterogeneity in search costs, which we documented in the previous subsection. Our aim is to determine the extent to which (i) the distribution of search costs varies across markets and (ii) this variation can be explained by observable market and population characteristics. To achieve this goal, we take estimated points of the search

[21] We have two combinations because consumers can search at most two stations.

[22] A different normalization would yield the same price cost margin of \$0.267 because what we exploit in the estimation is the variation in prices across time after taking the average differences in prices across firms. Similarly, the following analysis does not change quantitiatively if we choose a different minimum price.

cost CDFs across all markets, which are depicted in Figure A1 in Appendix, and use non-linear least squares regression to fit a parametric distribution. In the regression, we let the mean and variance of the distribution depend on market-level characteristics, which allows us to quantify the influence of these market characteristics on the distribution of search costs.

Table 3 presents the results of using non-linear least-squares to fit a lognormal (columns 1 through 3) CDF to the data points in all markets. We regard column 1 as the baseline specification, and columns 2 and 3 examine whether the results are robust to the exclusion of imprecisely estimated parameters.

Of first note is that across all specifications the mean income in a market is precisely estimated at the 5% level to positively affect the mean of the consumer search cost distribution.[23] This result is intuitive in two respects; income is positively correlated with the opportunity cost of time and people with higher income have a lower marginal utility of wealth (and therefore gain less utility from saving money on gasoline). Both of these effects imply higher search costs. In terms of magnitude, a 1% increase in household income increases the expected search costs by \$0.039 per gallon.[24]

We also find that the standard deviation of household income within a market positively affects the standard deviation of the search costs in a market. Thus, when household income becomes more dispersed within a market, the search cost distribution also becomes more dispersed. This finding further reinforces the link between income and the cost of search. Another robust pattern that emerges from these four specifications is that after controlling for income, higher mean age implies a lower mean of the search cost distribution at the 10% level of statistical significance. This result may reflect that retired people, who tend to be older than the average population, have a smaller opportunity cost of time, although we cannot rule out other explanations. Other variables, such as mean years of education and mean distance across stations, are not found to significantly affect the search cost distribution. The unconditional expectation of the search costs ($= \int c \, dF_c$) fitted on the lognormal distribution for a typical market with mean household income, mean education, mean age, and mean distance among stations is \$0.287 per gallon.[25]

Based on the estimated search cost distributions, the next section explores how heterogeneity

[23] The result is robust to the inclusion of the distance to the nearest highway exits.

[24] The results are robust to a different parametric distribution (column 4, normal CDF) and different measures of household income (median and median absolute deviation).

[25] The next section observes that due to the presence of non-searchers who pay zero search costs, the expected search costs paid is significantly smaller than this unconditional expectation of search costs.

of search costs affect price equilibrium by conducting policy experiments.

4 Policy Counterfactuals

This section adopts the parameter estimates of the second-stage search cost distribution to perform two sets of "what-if" experiments that quantify the influence of search costs on equilibrium prices in the retail gasoline markets. Each experiment compares a "baseline" CDF, which is calibrated to fit the parameter estimates in the previous section, to a "hypothetical" CDF, which alters the baseline CDF to reflect the impact of some policy. To compute the mean and standard deviation of the baseline lognormal search cost distribution, we use the structurally estimated model in the second stage regression and the average value across markets of the right-hand-side variables in the second stage regression.

To perform each policy experiment, we solve for the equilibrium price distributions that correspond to the baseline and hypothetical CDFs (policy 1) or number of stations (policy 2).[26] We assume the market-level characteristics, marginal costs, and the maximum willingness to pay do not change before and after the experiment. We normalize consumers' maximum willingness to pay to be \$2.779 per gallon, which is the highest price in the data.[27] In the data, the difference between the maximum willingness to pay and marginal costs is on average \$0.472, and therefore, in this section, assume that the marginal costs are \$2.307 (= \$2.779 − \$0.472) per gallon.

To analyze the effect of the policy counterfactuals on consumer and firm well-being, we compute the expected price paid, expected paid search costs, and the total number of searches. We calculate the total paid search costs at the market level by integrating the product of the search costs and

[26] To solve for the price distributions, we first compute the marginal gains from the ith search, Δ_i, based on the appropriate search cost CDF, an initial guess of q_i , the marginal costs, and the maximum willingness to pay. This first step yields $\tilde{q}_i$ a vector denoting the proportion of consumers with i price quotes, implied by the model. We then iterate the process until the initial starting values of q_i converge to a particular $\tilde{q}_i$. Based on this $\tilde{q}_i$, we generate 100 prices according to the price inverse function in equation (2). The results are robust to the number of generated prices.

[27] Normalizing the maximum willingness to pay to a certain constant is for the purpose of presention and does not affect quantitatively the following results; an alternative normalization with a different maximum willingness to pay, say \$4.000, simply shifts the equilibrium price distribution by \$1.221 (= \$4.000 − \$2.779).

the number of searches over the search cost CDF. Specifically,

$$E[c_{paid}] = \sum_{i=1}^{N}\{(i-1)\int_{Q_{N+1-i}}^{Q_{N+2-i}} cdF_c\}$$

$$\text{where } Q_i = 1 - \sum_{s=1}^{N+1-i} q_s \text{ if } N+1-i \geq 1 \text{ and } Q_i = 1 \text{ otherwise },$$

and N is the number of stations in that market. For instance, the expected search cost paid in a market with three station is

$$E[c_{paid}] = 2\int_{0}^{q_3} cdF_c + \int_{q_3}^{q_2+q_3} cdF_c,$$

and the first and the second term is the expected paid search costs for people who search twice and once, respectively. Similarly, the expected price paid is obtained by first calculating the expected price conditional on the number of times a consumer searches, and then integrating over the number of searches: $E[p_{paid}] = Epq_1 + \sum_{i=2}^{N}\{Ep - (\sum_{s=1}^{i-1}\Delta_s)\}q_i$. For instance, the expected price paid in a market with three stations is

$$E[p_{paid}] = \underbrace{Ep}_{\text{Expected price for non searchers}} *q_1 + \underbrace{(Ep - \Delta_1)}_{\text{Expected price for people who search once}} *q_2$$
$$+ \underbrace{(Ep - \Delta_1 - \Delta_2)}_{\text{Expected price for people who search twice}} *q_3.$$

To demonstrate how certain policies differentially affect consumers with different search costs, we present results for consumers in the 10th, 25th, 50th, and 75th percentiles of the search cost distribution.

4.1 Policy Experiment 1: A Change in the Costs of Search

We first examine an exogenous change in the cost of search, such as a technological advance in searching for gas prices or a government policy that publicizes gas prices on a website. Such a change would involve two aspects: change in the mean and change in the standard deviation of a distribution, and we discuss each aspect separately. In particular, we consider two scenarios in which the baseline search cost CDF (i) first-order stochastically dominates the hypothetical search cost CDF or (ii) is second-order stochastically dominated by the hypothetical search cost CDF.

Scenario (1): All consumers' cost of search decreases, and the baseline search cost CDF first-order stochastically dominates the hypothetical search cost distribution. This scenario considers a situation in which expected value of search costs decrease (or increase) for every consumer, while keeping the variability (i.e., standard deviation of the distribution) the same. A decrease in search costs would represent a situation in which consumers' search effort has been reduced due to technological developments, such as smartphones and related apps, that affect the ease of finding gasoline price quotes. As a consequence, the hypothetical search cost CDF (F'_c) is first-order stochastically dominated by the baseline search CDF, (F_c): $F'_c(t) > F_c(t)$ for any $t > 0$.[28] Given the significant relationship estimated in the previous section between search costs and household income, the counterfactual experiments can also be interpreted as a change in household income, rather than as a policy that directly alters the cost of search.

Table 4 presents the simulation results for a market with five firms for the baseline specification, a 20% decrease in search costs (case (1)), and a 20% increase in search costs (case (2)). To interpret the experiment as a change in household income, cases (1) and (2) and the baseline correspond to observationally equivalent markets except for the average household income, which is \$9,288, \$243,917 and \$62,270, respectively.[29] Below we mainly discuss the difference between the baseline and the 20% decrease in search costs in case (1) in the second column in Table 4. The expected price paid, on average, decreases by \$0.035 from \$2.573 (baseline). The decrease in the actual price paid differs across consumers with different search costs. For instance, consumers in the 50th percentile experience the largest decrease in the price paid ($-\$0.090 = \$2.523 - \$2.613$), whereas consumers in the 75th percentile experience the smallest decrease ($-\$0.025 = \$2.588 - \$2.613$) among the four categories of consumers (10%, 25%, 50%, and 75%tile).

We observe the policy change affects consumers with different search costs differently for other measures as well. The expected paid search costs decrease on average by \$0.003 from \$0.017. The decrease is the largest for consumers in the 25th percentile (−\$0.010), but people in the 50th percentile actually increase the paid search costs by \$0.062 due to an increased number of search. With respect to total consumer expenditure, which is the sum of expected price paid and paid search costs, consumers in the 25th percentile gain the most (−\$0.042) whereas consumers in the

[28] By contrast, an increase in search costs would represent a situation in which search behavior becomes more cumbersome due to an intentional price obfuscation by retailers (Ellison and Ellison 2009) or an installation of a government policy, such as one that prohibits the operation of price comparison gasoline websites (e.g., gasbuddy.com). In this scenario, the hypothetical search cost CDF (F'_c) first-order stochastically dominates the baseline CDF (F_c).

[29] This sample range in household income roughly corresponds to the observed mean household income's minimum and maximum (Table A1 in Appendix).

75th percentile gain the least (−\$0.025).

In Column 2, q_i demonstrates that, due to a decrease in search costs, the fraction of non-searchers decreases by 7.5 percentage points from 56.4%, and the remaining consumers who search one or more stations increase. An implication from these results is that although search costs change across consumers by the same percentage, there are heterogeneous effects across people with unique search costs.

To test the sensitivity of results, we redo the simulations with a different magnitude of change. Columns 4 and 5 in Table 4 show the results for a 50% decrease in search costs (case (3)) and a 50% increase in search costs (case (4)). The effect of the change in search costs on the equilibrium price distribution is qualitatively the same with case (1) and case (2), respectively, with more pronounced magnitudes.

Figures 4a and 4b present the simulated search cost CDF and equilibrium price CDF with 20% changes to the expected value of the search costs, respectively. These figures show that the case (1) price CDF is first-order stochastically dominated by the baseline price CDF. In turn, the expected price $E[p]$ decreases from \$2.613 to \$2.588 per gallon when search costs decrease by 20%. The lower bound of the price distribution drops by \$0.028 from \$2.438 to \$2.410, suggesting that the sample range becomes wider. Conversely, when consumers' search costs increase by 20% the the baseline price CDF is first-order stochastically dominated by the hypothetical equilibrium price CDF.[30]

Overall, this exercise confirms our intuition that an exogenous shifts in search cost CDF in the FOSD sense lead to a new price equilibrium in which all consumers benefit from lower prices, but the magnitude of the impacts, such as the differences in total expenditure, differs across consumers with different search costs.

Scenario (2): Hypothetical search cost distribution second-order stochastically dominates (SOSD) the baseline search cost distribution. This scenario considers a situation in which consumers' search costs become less heterogeneous (but not completely homogeneous); the expected search costs do not change, but the hypothetical search cost CDF (F_c') has a lower standard deviation. More precisely, we consider a case in which F_c' second-order stochastically dominates the baseline search CDF (F_c), and therefore, $\int c\ dF_c' = \int c\ dF_c$ and $\int_0^x F_c(t)dt \geq \int_0^x F_c'(t)dt$ for all x.

[30]Figures A2a and A2b in Appendix show the pattern holds for the case in which search cost mean changes by 50%.

To perform this experiment, the standard deviation parameter of the lognormal CDF, σ, for the hypothetical distribution, F'_c, is set to be 15% lower than the standard deviation for the baseline lognormal distribution, F_c. We then calculate the mean parameter, μ, for the hypothetical distribution that yields the same unconditional expected search costs, $\int c \, dF_c = \int c \, dF'_c = \$0.287$ per gallon of gasoline.[31] Using F_c and F'_c we simulate gas stations' optimal pricing decisions under the baseline and hypothetical scenarios.[32]

Figures 5a and 5b present the simulated search and price CDFs when the estimated standard deviation parameter is decreased (or increased) by 15%. Prices become less dispersed when the standard deviation parameter decreases, because as search costs become more homogeneous, firms have less incentive to set low prices to sell to consumers with relatively low search costs. Figures 6a and 6b conduct the same experiment, but the standard deviation is changed by 20%. Figure 6b depicts a striking result – price dispersion completely disappears as firms maximize profits by setting the monopoly price. This result is akin to Diamond (1971)'s monopoly equilibrium; however, it arises in a non-sequential search environment, and all consumer search costs need not be equal. Table A3 in Appendix presents the quantitative results. When the standard deviation is reduced by 15%, consumers in the 10th percentile of the search cost distribution only search once and consumers in higher parts do not search at all. When the standard deviation is reduced by 20% no consumers search. In the former case, there still exists price dispersion, as consumers at the low end of the distribution still search and such a behavior benefits consumers at the high end of search cost. In the latter case, consumers in the low end of the distribution no longer search, and all firms' profit-maximizing strategy is to set the monopoly price.

That firms may all set the monopoly price when consumer search costs are sufficiently homogenous, but not identical, has an important policy implication; a policy or firms' strategy that lowers both the expected value and variance of search costs may have the unintended consequence of having all firms increase their price to the monopoly price. The reason for this result is that firms in our market face a trade-off between setting a low price and selling to searchers and non-searchers and setting a high price and selling to only people who search with low intensity. When search costs become more homogeneous the trade-off disappears because the sales from low search costs people becomes too small to make the expected profit the same across different prices. To confirm

[31] Note that we distinguish the mean parameter μ and the expected value of the lognormal distribution, which is $e^{\mu+\frac{\sigma^2}{2}}$.

[32] We again assume the number of gas stations to be five. We obtain similar results for market structures with different numbers of firms.

this point, we run a variant of the last policy experiment; in addition to reducing the standard deviation of search costs, we also decrease the expected value of the search cost distribution. Figures A3a and A3b in Appendix presents the results of decreasing the expected value of the search cost distribution by 10% and reducing the standard deviation by 20% and 22%, respectively. When the standard deviation is reduced by 20%, we have a price dispersion unlike the previous case in Figure 6b because it is cheaper to search due to a reduced search costs by 10%. When the standard deviation is reduced by 22%, however, no consumers search even when the expected value of the search costs decreases by 10%.

4.2 Policy Experiment 2: A Change in Market Structure

Now we investigate how, holding the search cost distribution constant, different market structure affects the equilibrium price distribution and search behavior differently. This experiment informs how firms and consumers respond to an increase in competition via entry of firms into the retail gasoline market.

To conduct this experiment, we assume that exogenous changes in market structure do not affect the distribution of consumer search costs, and use the same mean and standard deviation for the lognormal search costs distribution we estimated in the previous section and used in the experiment above.

Figure 7 presents the simulated price distribution for hypothetical markets with two, three, six, and twelve gas stations. Two patterns emerge from this figure. First, the minimum price decreases as the number of stations increase, and, as the maximum price remains fixed at \$2.779, the price range ($= p_{\max} - p_{\min}$) increases in the number of stations. Second, beyond three stations, the difference in the price distributions across markets becomes considerably smaller. Although the minimum price declines when a market becomes more competitive, those who do not search are worse off in less concentrated markets with more than three firms. Indeed, Figure 7 shows that, for prices below \$2.48, the simulated price CDF for a market with 12 stations is flatter than the CDF with six stations. This pattern implies that the lower minimum price in a market with 12 stations will be compensated by a steeper CDF above \$2.48, which means that consumers with high search costs may face higher prices when the number of firms increase from six to twelve.

Figure 8a further analyzes these points in detail by displaying the summary statistics by market structure. The figure demonstrates how equilibrium price dispersion and paid search costs change with the number of firms. Again, the minimum price declines monotonically with the number of gas stations in a market. Meanwhile, the unconditional expected price $E[p] = \int p \ dF_p$, the price when consumers randomly pick a gas station, attains its minimum at a market with four stations. That the pricing in local geographic markets becomes relatively competitive after three or four entrants is similar to the findings in Bresnahan and Reiss (1991). Figure 8a suggests that, beyond four stations, the expected price, $E[p]$, increases in the number of stations. This result diverges from a canonical Cournot or differentiated Bertrand model, which predicts that an increase in the number of firms monotonically reduces prices.

We also calculate the expected price paid after conditioning on the number of times a consumer searches. Figure 8a shows the expected price paid is lower than the expected price, as people who search once or more push down the average market price paid. Table A4 in Appendix shows the expected price paid attains its minimum at a market with 13 stations. We then calculate the total expenditure for consumers by adding the expected price paid and paid search cost. Figure 8a and Table A4 in Appendix show that the total expenditure attains its minimum when the number of gas stations is seven, and is smaller than with 13 stations. This result is a natural one, as the expected paid search costs increase monotonically with the number of stations.[33]

Interestingly, we observe a non-monotonic relationship between the standard deviation of prices and the number of stations. Table A4 and Figure 8b illustrate that the standard deviation flattens out after a market with seven stations, and it in fact attains its maximum at a market with $17, 18$, and 19 stations, and thereafter decreases. Thus one of the measures of price dispersion, the standard deviation of prices, is not monotonic in the number of stations, which has two implications. First, this non-monotonicity contrasts the theoretically documented monotonic relationship between the number of stations and the gains from search $E[p - p_{\min}]$ (e.g., Chandra and Tappata 2011), which is often used as an alternative measure of price dispersion. Second, a linear regression of the standard deviation of prices on the number of firms (and controls) is unlikely to be rich enough to learn the relationship between price dispersion and search behavior.

Turning to how the change in market structure affects consumers with different search costs, Table 5 shows consumers in the 10th percentile benefit from increased competition, whereas consumers in the 75th percentile do not, and are sometimes worse off. For example, a 10th percentile consumer in a market with 12 stations (last column) pays \$0.015 (=1.5 cents) per gallon less than a

[33] Figure 8b demonstrates that the expected paid search costs increase with the number of stations. The fraction of people who never search (q_1) decreases with the number of stations, reflecting that the gain from the first search increases with the number of stations in a market. On the other hand, the fraction of "shoppers" is 32.0%, 23.9%, 9.2%, and 2.0% for a market with two, three, six, and 12 stations, respectively.

consumer with the same search costs in a market with five stations (baseline). On the other hand, a 75th percentile consumer pays \$0.003 per gallon more when moving from five to 12 stations. The expected paid search costs increase for consumers in the 10th percentile because the number of searches increase from four to five, whereas the expected paid search costs do not change for consumers in the 75th percentile because the number of search remains zero. Overall, when the number of gas stations increase from five to 12, the expected total expenditure, which is a proxy for consumer utility, does not change noticeably at the market level. The reason is that the decrease in price paid ($-\$0.003 = \$2.570 - \$2.573$) is offset by the increase in paid search costs ($\$0.003 = \$0.020 - \$0.017$). If we look at the distributional consequences, however, the benefits from the increased number of stations differ by the percentile of search cost distribution. For instance, the expected total expenditure for a consumer in the 10th and 75th percentiles decreases by \$0.005 from \$2.531 and increases by \$0.003 from \$2.613, respectively, when the number of stations changes from five to 12.

Overall, we find that the market-level expected price paid decreases in the number of firms, but consumers with high search costs may be worse off from an increased number of firms.

5 Conclusions

This paper documents the heterogeneity of search costs across markets and explores how heterogeneous search costs and market structure interact to produce equilibrium price dispersion in the U.S. retail gasoline industry. Based on a non-sequential search model and daily price data, we recover the distribution of search costs for a set of geographically isolated markets. We use the estimated search costs to conduct two counterfactual policy experiments. First, we examine the effect of FOSD and SOSD shifts in the search cost distribution. Second, we investigate the implications of market structure into gasoline markets. For both experiments, we examine the effect on the equilibrium price distribution and quantify the distributional consequences for consumers within four different percentiles of the search cost distribution.

The paper has three major findings. First, the distribution of search costs varies substantially across markets and some market and population characteristics, such as household income, are able to explain some of this variation. Second, we confirm that the search cost distribution needs to be sufficiently heterogeneous to generate equilibrium price dispersion. Finally, although the market-level expected price paid decreases in the number of firms, we find that consumers with high search costs may be worse off with an increased number of gas stations.

This study includes some simplifying assumptions, and relaxing these provide a future research agenda. First, studying the effect of entry on pricing assumes the change in market structure is exogenous. In the long run, however, market structure is determined through endogenous entry and exit, which is driven by the profitability of a market. Our work serves as a first step toward understanding the short-run effect of market structure on pricing. Second, the model assumes that the quantity of gasoline purchased is inelastic to the change in prices. While in the short-run this may be true, in the long run people may consume less gasoline or substitute from driving to other transportation methods when the retail gasoline price increases. Third, we assumed a lognormal search cost distribution. Although this assumption allows us to explore hypothetical policy counterfactuals, the quantitative results in the simulation are subject to this approximation. Finally, we abstract from multi-station pricing under joint ownership due to data limitation. This assumption, however, is inadequate to consider the effect of mergers for the retail gasoline markets. Allowing for multi-station ownership is an important topic of future research.

Appendix: equilibrium price density

Following Moraga-González and Wildenbeest (2008), applying the implicit function theorem to equation (1) yields the density for equilibrium price as

$$f_p(p) = \frac{\sum_{i=1}^{N} i q_i (1 - F_p(p))^{i-1}}{(p-r)\sum_{i=1}^{N} i(i-1) q_i (1 - F_p(p))^{i-2}} \ ,$$

and $F_p(p_l)$ solves $(p_l - r)[\sum_{i=1}^{N} \frac{iq_i}{N}(1 - F_p(p_l))^{i-1}] = \frac{q_1(\bar{p}-r)}{N}$ for all $l = 2, .., M-1$.

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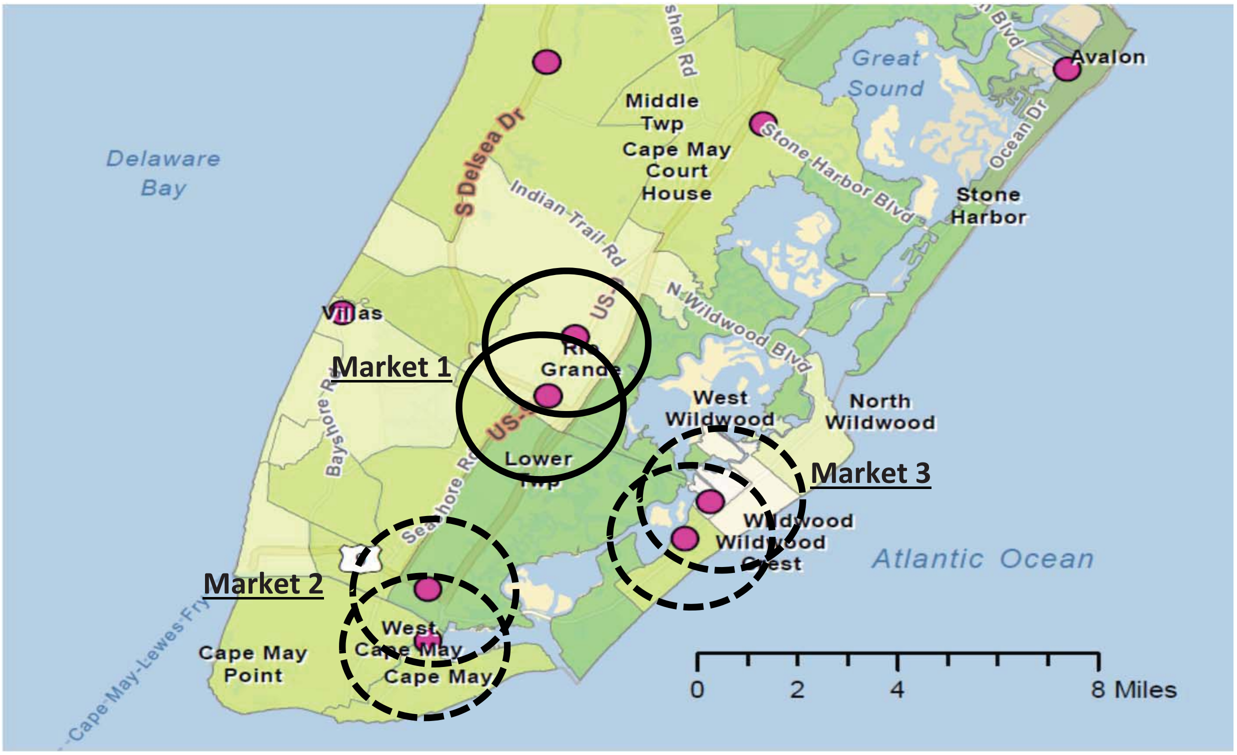
Figure 1

Example of 1.5 Mile Radius Isolated Markets at Capemay, New Jersey



Note: A small red circle represents a gas station location. A large black circle has a 1.5 mile radius. Different terrain colors represent different census tracts. Out of Market 1, 2, and 3 with more than one station, only Market 1 qualifies as an "isolated" market in our sample because (1) every station is located within 1.5 mile from all other stations and (2) every gas station in the market belongs to the same census tract (Rio Grande for Market 1).

Figure 2

Distribution of Number of Stations by Isolated Markets (1.5 Miles Radius, 2006-7)

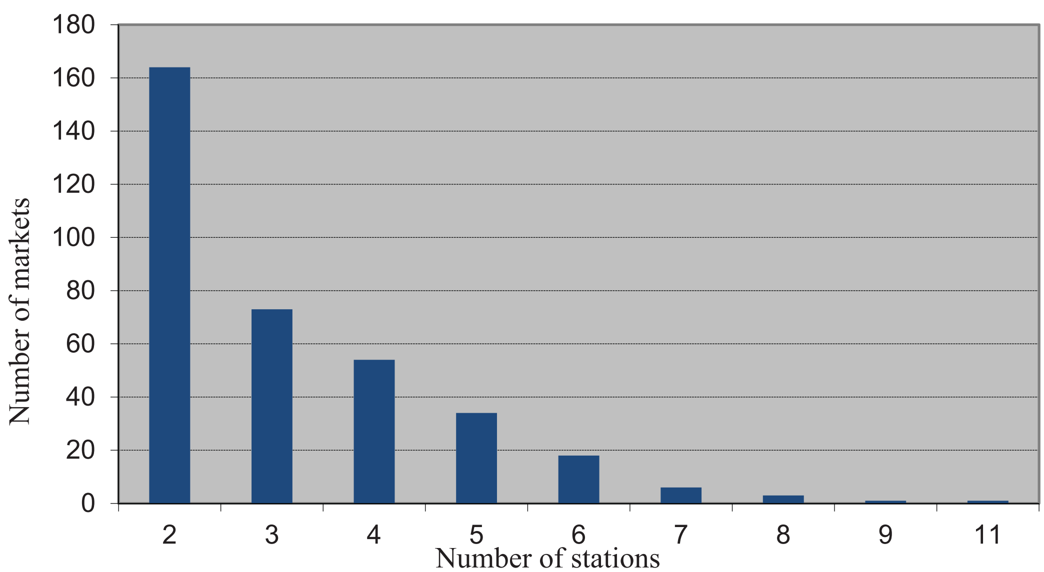
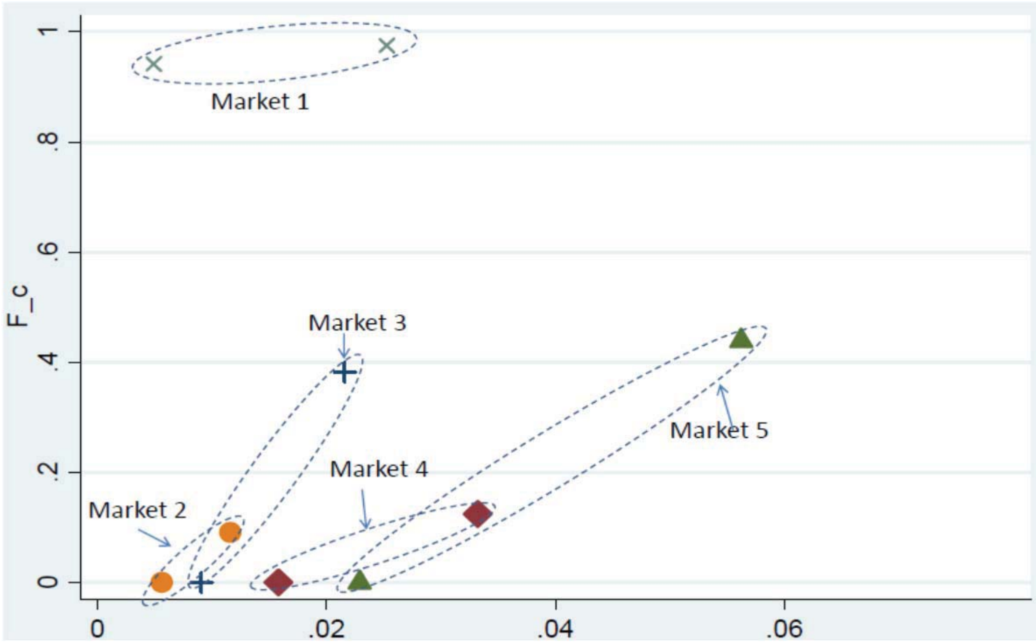


Figure 3a

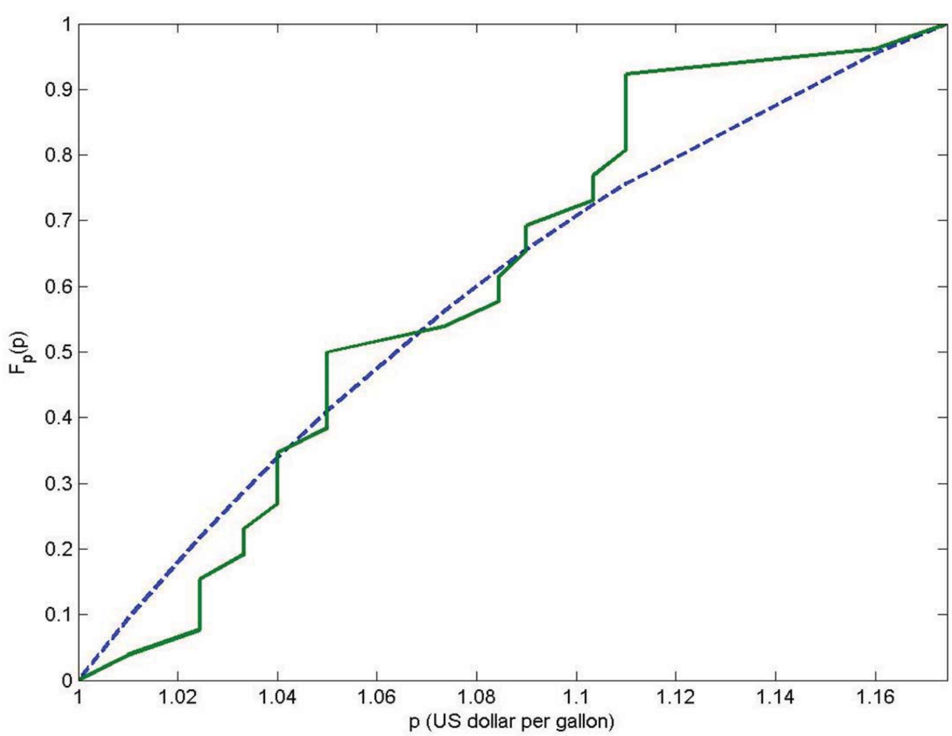
Estimated Search Costs CDF, February 27th through March 28th, 2007



Note: The horizontal axis is the search cost in dollar per gallon. This Figure plots the combination of estimated $\varDelta_i$ and $Fc(\varDelta_i)$ for each of five geographically isolated markets in Texas. All markets have three stations. For a given market, the right and left points correspond to $(\varDelta_1, Fc(\varDelta_1))$ and $(\varDelta_2, Fc(\varDelta_2))$, respectively.

Figure 3b

Empirical and Estimated (dash) Price Distribution, February 27th through March 28th, 2007



Note: A market in Texas. The minimum price in this market is rescaled to $1 per gallon.

Figure 4a

Search cost cdf with 5 stations and 20% change in the expected value of search cost distribution

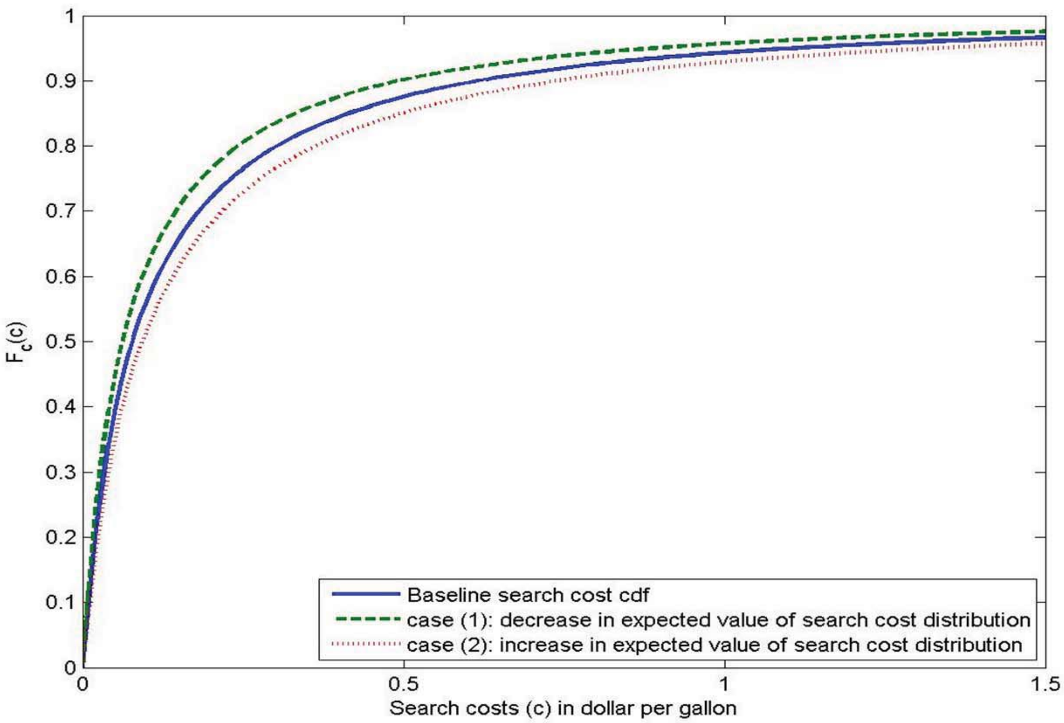


Figure 4b

Simulated price distribution with 5 stations and 20 percent change in the expected value fo search cost cdf

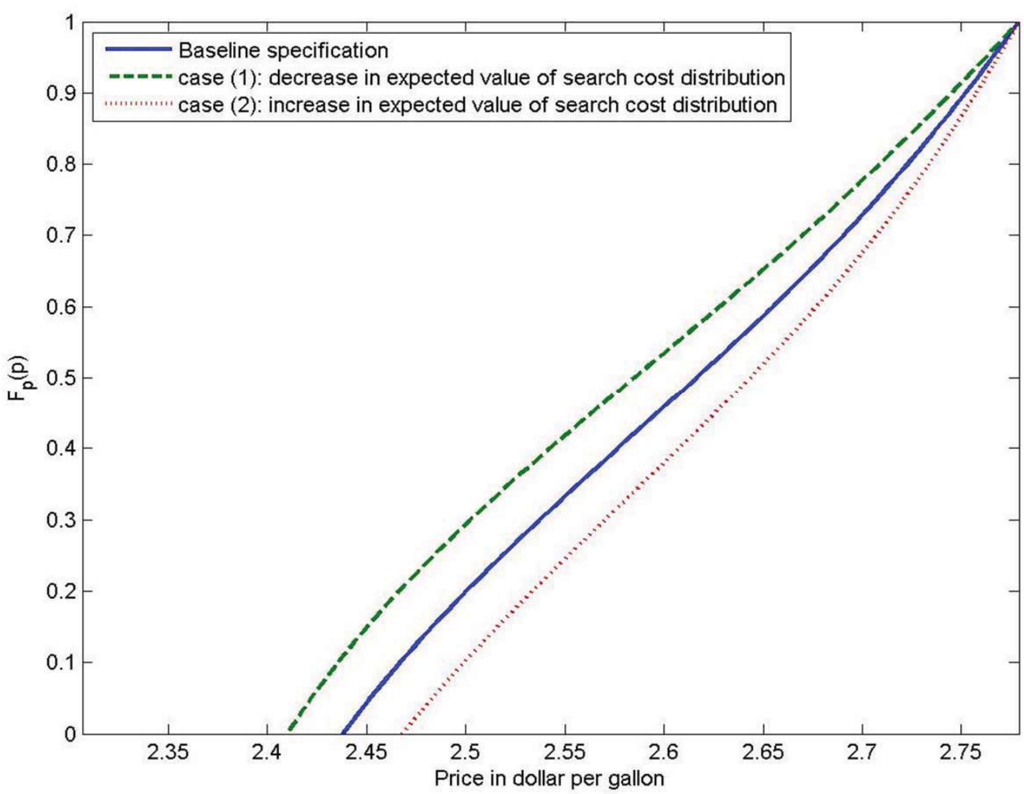


Figure 5a

Search CDF with 5 stations and 15 percent change in standard deviation

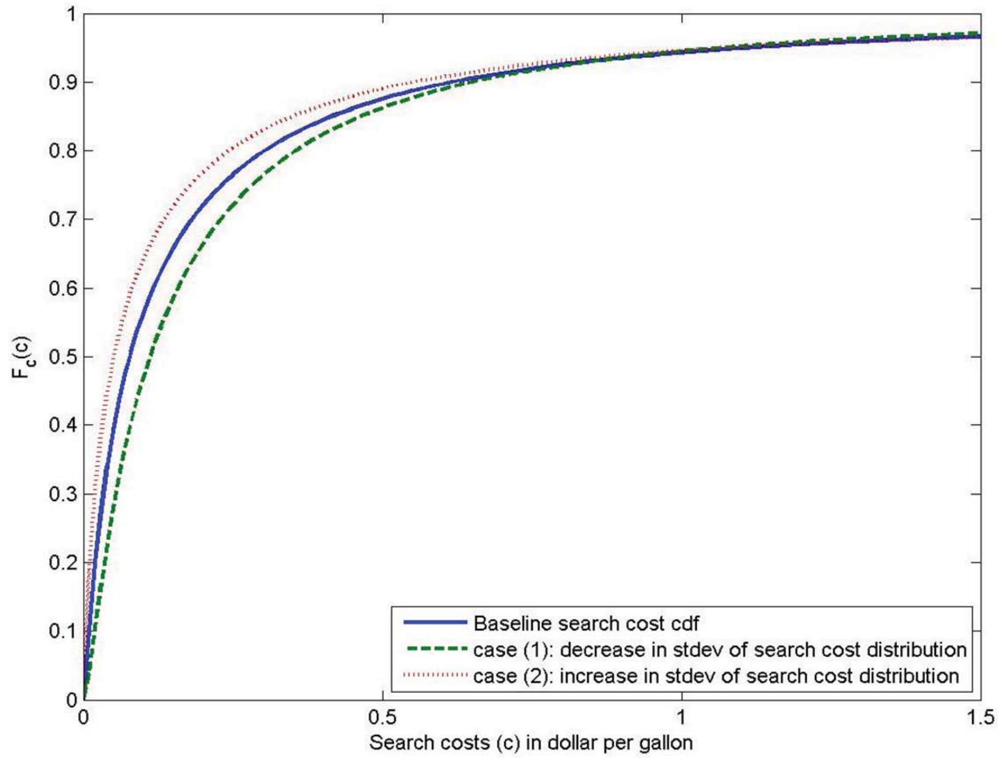


Figure 5b

Simulated price cdf with 5 stations and 15 percent change in standard deviation of search cdf

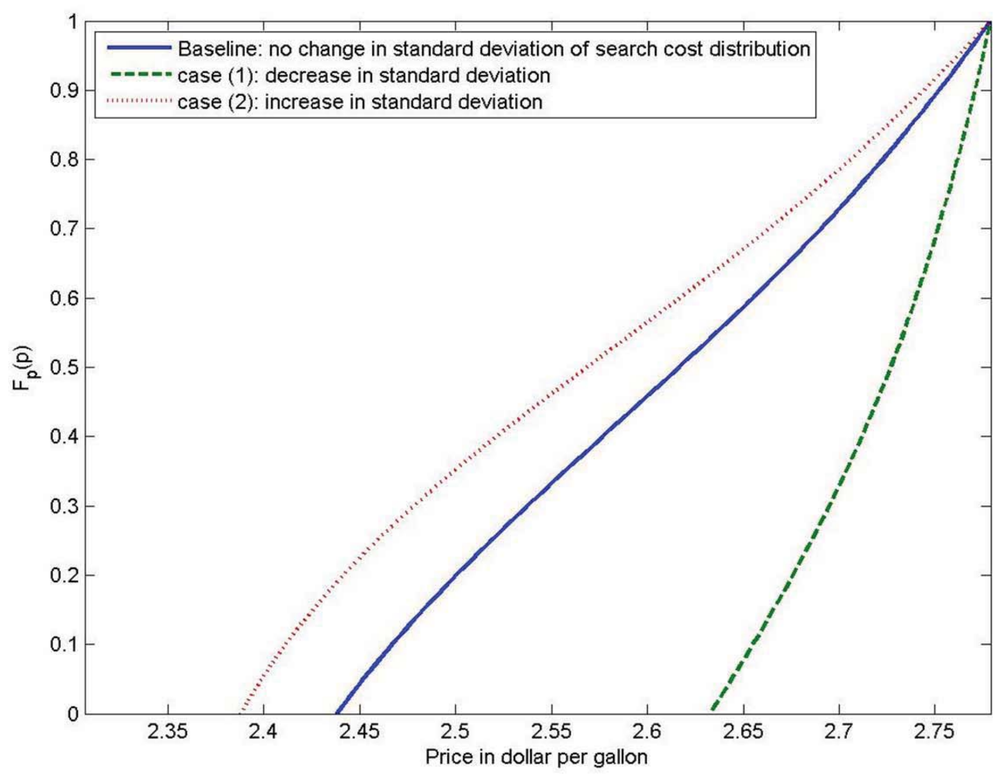


Figure 6a
Search CDF with 5 stations and 20 percent change in standard deviation

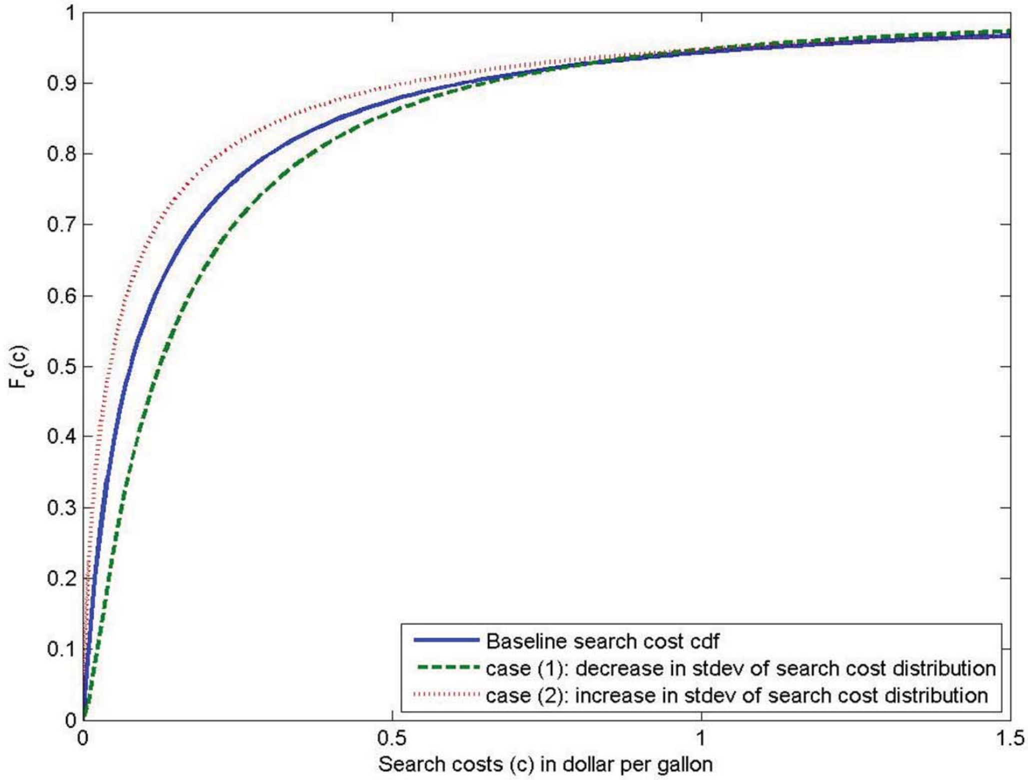


Figure 6b
Simulated price cdf with 5 stations and 20 percent change in standard deviation of search cdf

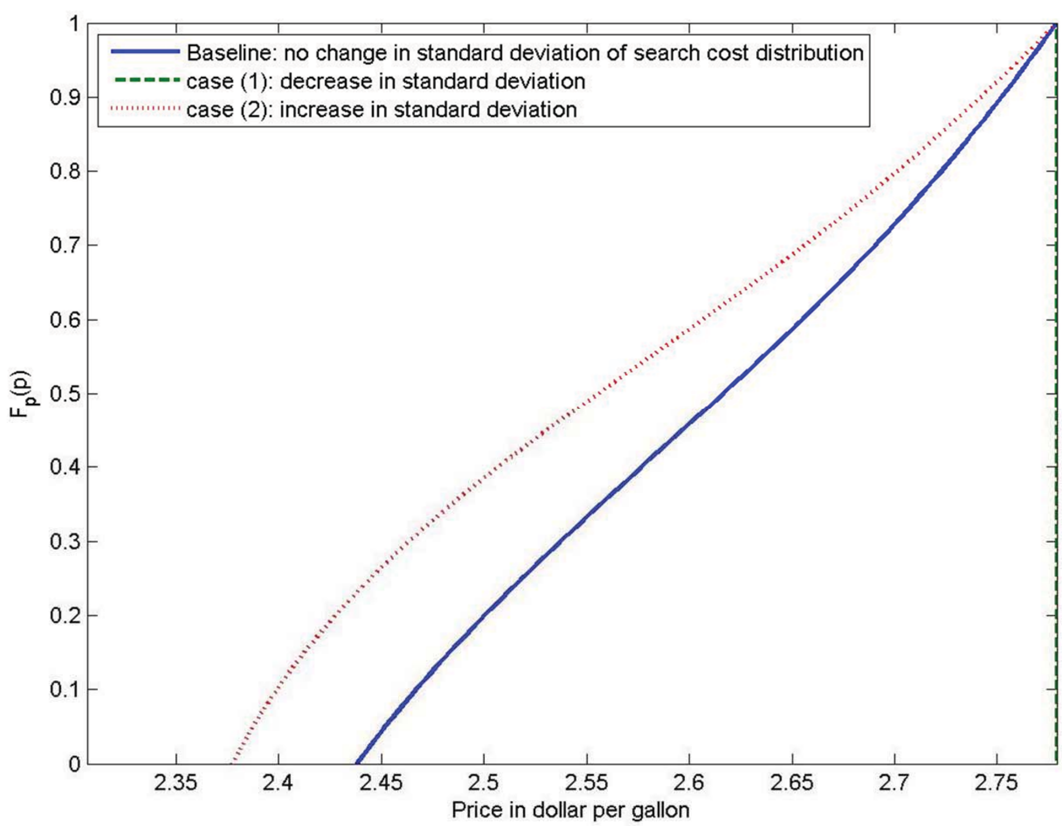


Figure 7

Simulated equilibrium price cdf by market structure

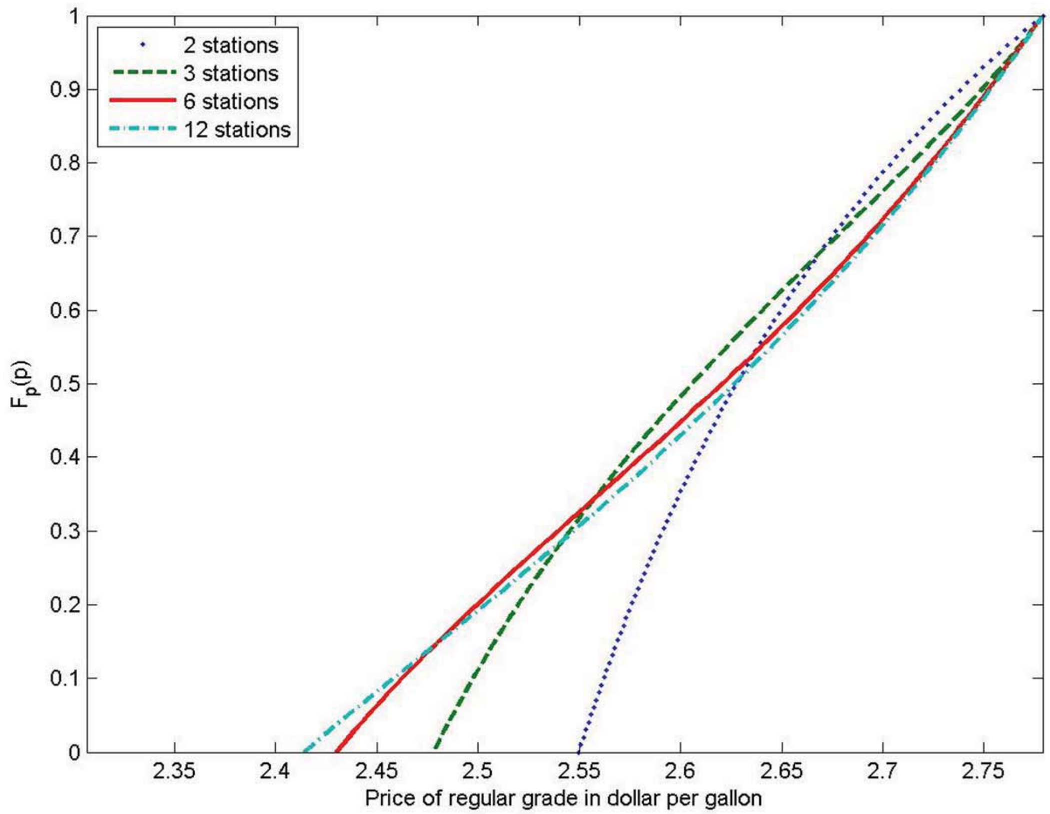


Figure 8a Simulated Equilibrium Pices by Market Structure

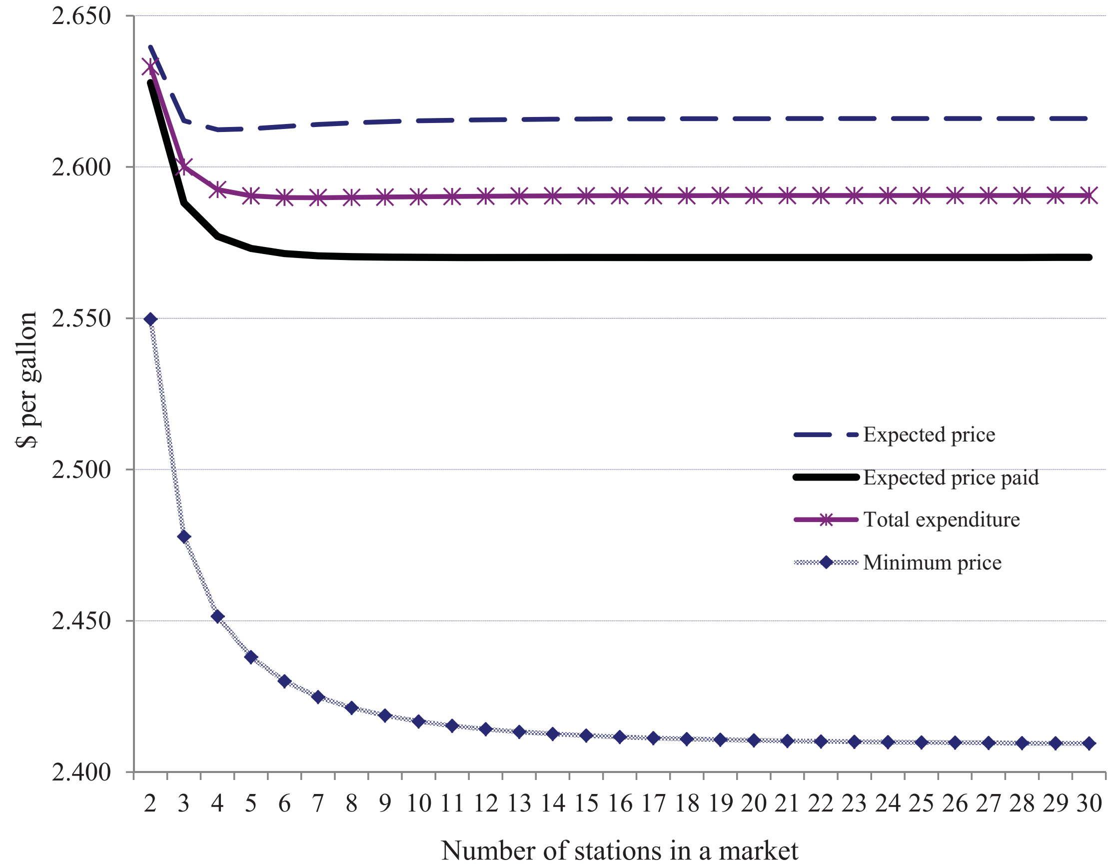


Figure 8b Simulated Equilibrium Search Costs Paid and Standard Deviation of Price

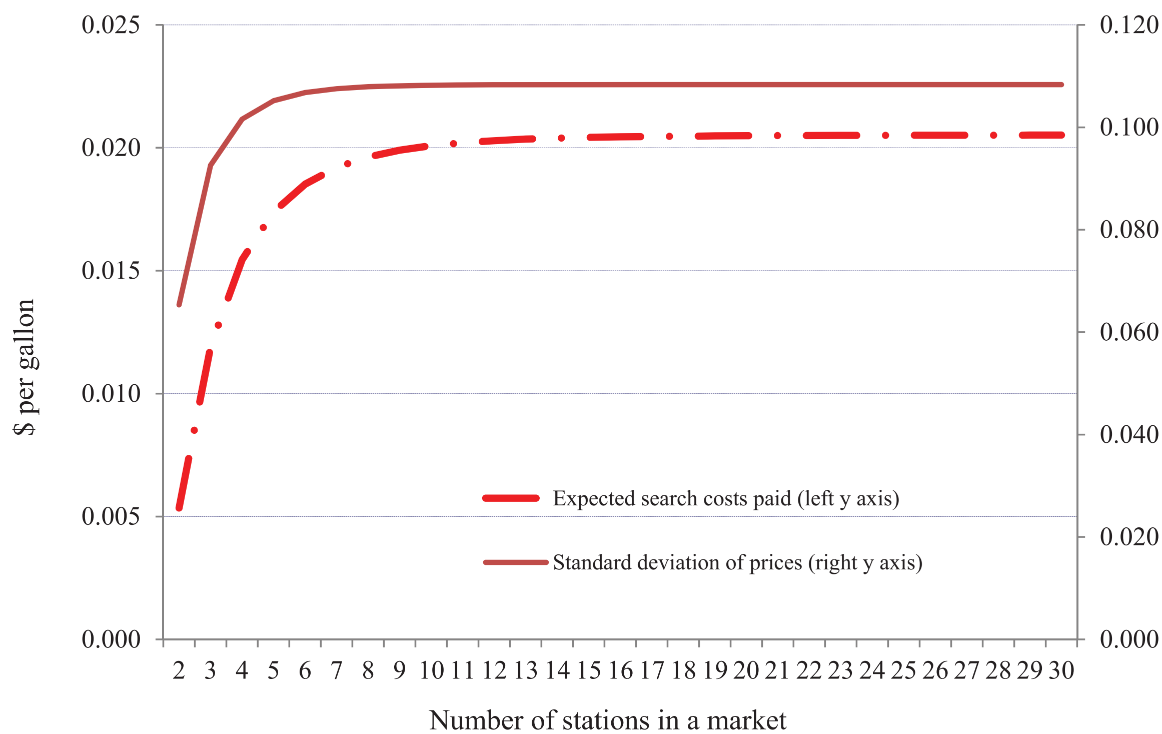


Table 1

Price Dispersion by Market Structure

	Regular-grade gas prices					Daily crude oil prices
	Markets with 2 stations	Markets with 3 stations	Markets with 4 stations	Markets with 5 stations	All markets (excluding monopoly markets)	All markets
Minimum price	2.538	2.593	2.482	2.393	2.517	1.343
Maximum price	2.771	2.868	2.758	2.673	2.779	1.526
Mean price	2.682	2.764	2.649	2.549	2.677	1.427
Sample range	0.243	0.275	0.276	0.279	0.262	0.183
Standard deviation	0.065	0.075	0.068	0.062	0.067	0.051
Number of observations	164	73	54	34	354	30

Note: The unit of observation for columns regarding regular gas prices is a market; the above statistics on prices are produced by taking the average across markets for a given market structure. The retail gasoline price observations are from 354 isolated markets from February 27th through March 28th, 2007. Crude oil prices are the WTI crude oil closing prices on the NYMEX over the same date range. The number of observations for crude oil is 30 because we are looking at 30 days, and this crude oil price is the same for all markets on each day.

Table 2
Estimated Search Cost CDF for All Markets

	Mean	Std. Dev	Min	Max	# of Obs.
Proportion of people with *i* price quotes (q_i)					
q_1	0.630	0.172	0.086	0.939	354
q_2	0.331	0.156	0.027	0.914	354
q_3	0.087	0.144	0.000	0.729	190
q_4	0.079	0.103	0.000	0.382	117
q_5	0.089	0.091	0.000	0.321	63
q_6	0.104	0.092	0.000	0.287	29
q_7	0.069	0.077	0.000	0.227	11
q_8	0.084	0.077	0.000	0.157	5
q_9	0.153	0.217	0.000	0.307	2
q_{10}	0.000	.	0.000	0.000	1
q_{11}	0.171	.	0.171	0.171	1
Marginal expected savings from searching *i* +1 versus *i* stations (Δ_i)					
Δ_1	0.037	0.014	0.007	0.090	354
Δ_2	0.017	0.006	0.003	0.034	354
Δ_3	0.010	0.003	0.003	0.019	190
Δ_4	0.007	0.002	0.004	0.011	117
Δ_5	0.005	0.002	0.003	0.008	63
Δ_6	0.004	0.001	0.002	0.007	29
Δ_7	0.003	0.001	0.002	0.006	11
Δ_8	0.004	0.001	0.003	0.005	5
Δ_9	0.004	.	0.004	0.004	2
Δ_{10}	0.003	.	0.003	0.003	1
Marginal cost	0.733	0.216	0.015	0.995	354

Table 3

Nonlinear Least Square Estimation of Search Cost Cumulative Distribution

Distributional assumption	Lognormal			Normal
	(1)	(2)	(3)	(4)
Mean of distribution				
Constant	-6.119	-8.306	-6.259	-0.012
	1.727	1.210	1.712	0.055
Mean income	0.506	0.671	0.535	0.013
	0.196	0.168	0.193	0.006
Mean years of education	0.177		0.122	0.001
	0.693		0.693	0.020
Mean age	-0.641	-0.641	-0.666	-0.019
	0.370	0.370	0.374	0.011
Mean distance among stations	-0.181	-0.181		-0.005
	0.191	0.191		0.006
Standard deviation of distribution				
Constant	-3.105	-3.105	-3.122	-5.879
	1.244	1.244	1.250	1.378
Standard deviation of income	0.336	0.336	0.338	0.263
	0.110	0.110	0.110	0.124
Mean squared error	20.231	20.328	20.260	21.045
Number of observations	773	773	773	773

Note: Parameter estimates and standard errors are in the upper and lower row of each variable, respectively. The regressors are in logs.

Table 4

The Effect of Change in Search Costs on Equilibrium Price Distribution: FOSD

	Baseline	(1) 20% decrease	(2) 20% increase	(3) 50% decrease	(4) 50% increase
Minimum price	**2.438**	**-0.028**	0.030	-0.068	0.081
Maximum price	2.779	0.000	0.000	0.000	0.000
Expected price (Ep)	**2.613**	**-0.025**	0.022	-0.070	0.054
Expected price paid	**2.573**	**-0.035**	0.032	-0.099	0.076
people with 10%tile search costs	2.492	-0.032	0.043	-0.081	0.091
people with 25%tile search costs	2.522	-0.031	0.059	-0.100	0.101
people with 50%tile search costs	**2.613**	**-0.090**	0.022	-0.141	0.054
people with 75%tile search costs	**2.613**	**-0.025**	0.022	-0.070	0.054
Sample range (p_{max} - p_{min})	0.341	0.028	-0.030	0.068	-0.081
Standard deviation of price	0.105	0.009	-0.010	0.021	-0.026
Expected search costs	0.287	-0.057	0.057	-0.143	0.144
Expected paid search costs	**0.017**	**-0.003**	0.004	-0.008	0.009
people with 10%tile search costs	0.039	-0.008	-0.004	-0.019	0.005
people with 25%tile search costs	**0.052**	**-0.010**	-0.021	-0.013	-0.013
people with 50%tile search costs	**0**	**0.062**	0.000	0.039	0.000
people with 75%tile search costs	0	0	0	0.000	0.000
Expected total expenditure	2.590	-0.038	0.036	-0.107	0.085
people with 10%tile search costs	2.531	-0.039	0.039	-0.101	0.096
people with 25%tile search costs	2.575	**-0.042**	0.037	-0.114	0.087
people with 50%tile search costs	2.613	-0.028	0.022	-0.103	0.054
people with 75%tile search costs	2.613	**-0.025**	0.022	-0.070	0.054
Average number of search	1.027	0.206	-0.178	0.600	-0.412
people with 10%tile search costs	4	0	-1	0	-1
people with 25%tile search costs	2	0	-1	1	-1
people with 50%tile search costs	0	1	0	1	0
people with 75%tile search costs	0	0	0	0	0
Average marginal costs	2.307	0.000	0.000	0.000	0.000
Expected profit margin	0.266	-0.035	0.032	-0.098	0.076
Proportion of people with *i* price quotes (q_i)					
q_1	**0.564**	**-0.075**	0.068	-0.210	0.160
q_2	0.154	0.017	-0.017	0.038	-0.045
q_3	0.096	0.017	-0.014	0.045	-0.035
q_4	0.061	0.012	-0.011	0.036	-0.025
q_5	**0.124**	**0.030**	-0.024	0.092	-0.056
Marginal expected savings from searching $i+1$ versus i stations (Δ_i)					
Δ_1	0.060	**0.005**	-0.006	0.011	-0.016
Δ_2	0.031	0.001	-0.003	0.001	-0.007
Δ_3	0.018	0.001	-0.001	0.000	-0.003
Δ_4	0.012	0.000	0.000	-0.001	-0.001

Note: The number of stations is five. We assume the marginal costs are $2.307 per gallon. The number of simulated price observations is 100. Columns (1) through (4) measure the increase from the corresponding value in the baseline specification.

Table 5

The Effect of Change in Market Structure on Equilibrium Price Distribution

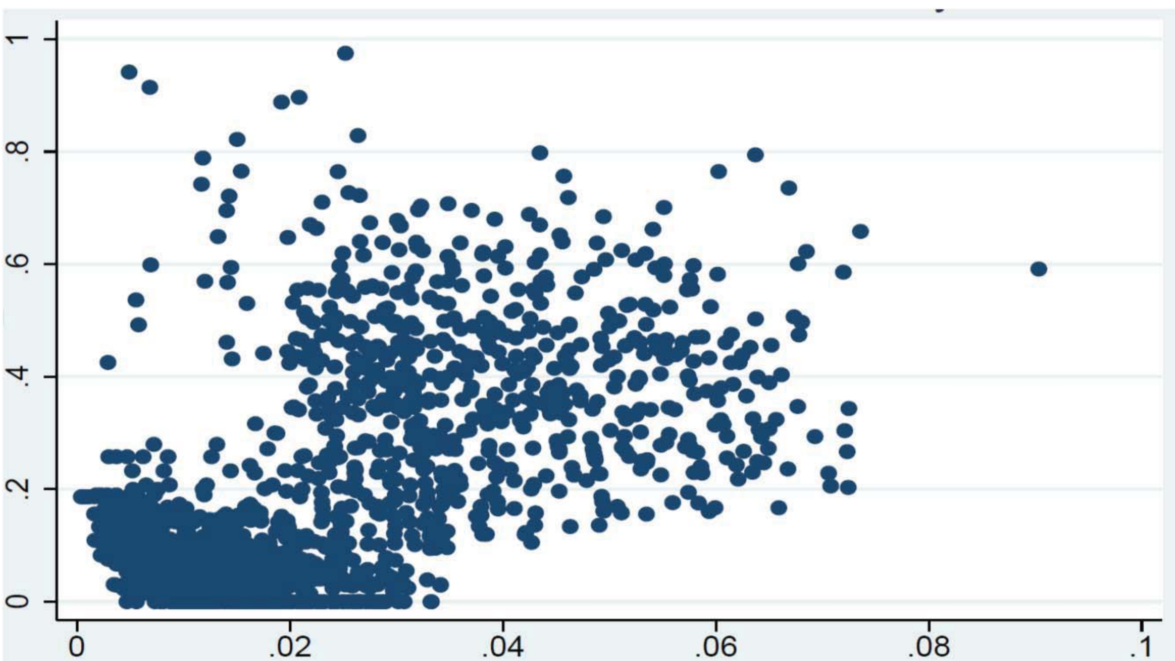
	Baseline 5 stations	(1) 2 stations	(2) 3 stations	(3) 6 stations	(4) 12 stations
Minimum price	2.438	0.112	0.040	-0.008	-0.024
Maximum price	2.779	0.000	0.000	0.000	0.000
Expected price (Ep)	2.613	0.027	0.002	0.000	0.003
Expected price paid	**2.573**	0.055	0.015	**-0.002**	**-0.003**
people with 10%tile search costs	**2.492**	0.111	0.046	**-0.003**	**-0.015**
people with 25%tile search costs	2.522	0.081	0.041	-0.001	-0.001
people with 50%tile search costs	2.613	0.027	0.002	0.000	0.003
people with 75%tile search costs	**2.613**	0.027	0.002	**0.000**	**0.003**
Sample range (p_{max} - p_{min})	0.341	-0.112	-0.040	0.008	0.024
Standard deviation of price	0.105	-0.040	-0.012	0.002	0.003
Expected search costs	0.287	0.000	0.000	0.000	0.000
Expected paid search costs	**0.017**	-0.012	-0.005	0.002	**0.003**
people with 10%tile search costs	**0.039**	-0.029	-0.019	**0.000**	**0.010**
people with 25%tile search costs	0.052	-0.026	-0.026	0.000	0.000
people with 50%tile search costs	0.000	0.000	0.000	0.000	0.000
people with 75%tile search costs	**0.000**	0.000	0.000	**0.000**	**0.000**
Expected total expenditure	**2.590**	0.043	0.010	0.000	**0.000**
people with 10%tile search costs	**2.531**	0.082	0.027	**-0.003**	**-0.005**
people with 25%tile search costs	2.575	0.054	0.014	-0.002	-0.001
people with 50%tile search costs	2.613	0.027	0.002	0.000	0.003
people with 75%tile search costs	**2.613**	0.027	0.002	**0.000**	**0.003**
Average number of search	1.027	-0.707	-0.384	0.118	0.423
people with 10%tile search costs	4	-3	-2	0	1
people with 25%tile search costs	2	-1	-1	0	0
people with 50%tile search costs	0	0	0	0	0
people with 75%tile search costs	0	0	0	0	0
Average marginal cost	2.307	0.000	0.000	0.000	0.000
Expected profit margin	0.266	0.055	0.016	-0.001	-0.003

Note: We assume the marginal costs are $2.307 per gallon. The number of simulated price observations is 100. Columns (1) through (4) measure the increase from the corresponding value in the baseline specification.

Appendix Figures and Tables

Figure A1

Estimated Search Costs CDF, February 27th through March 28th, 2007: All Markets



Note: The horizontal axis is the search cost per station in dollar per gallon.

Figure A2a

Search cost cdf with 5 stations and 50% change in the expected value of search cost distribution

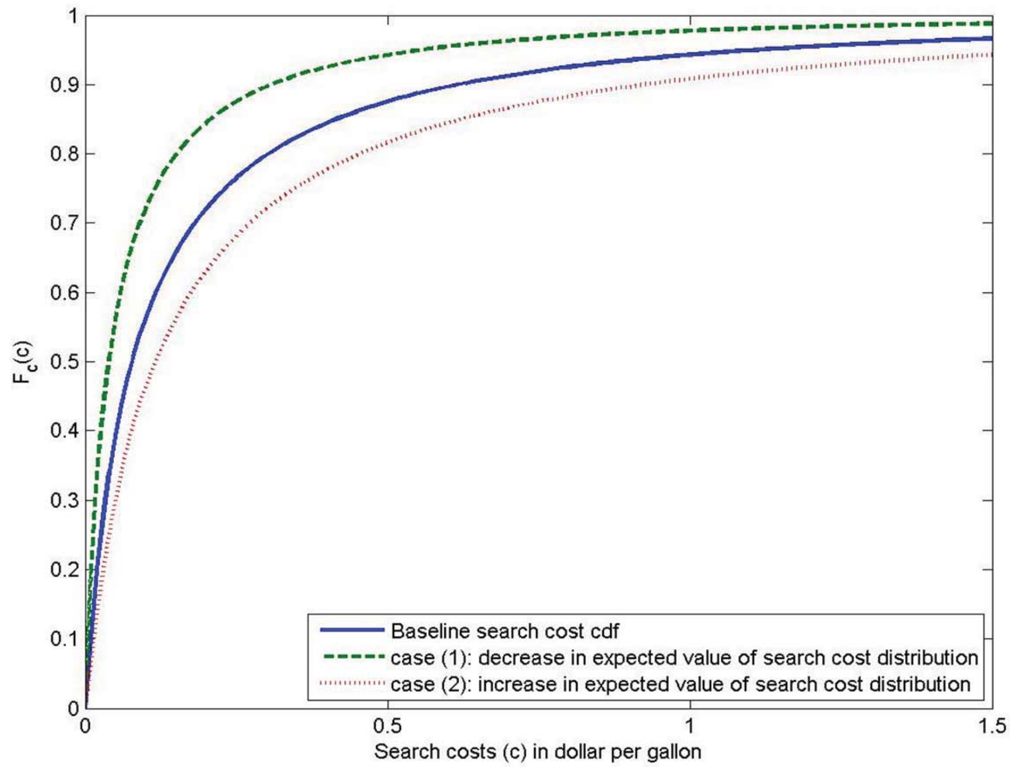


Figure A2b

Simulated price distribution with 5 stations and 50 percent change in the expected value of search cost distribution

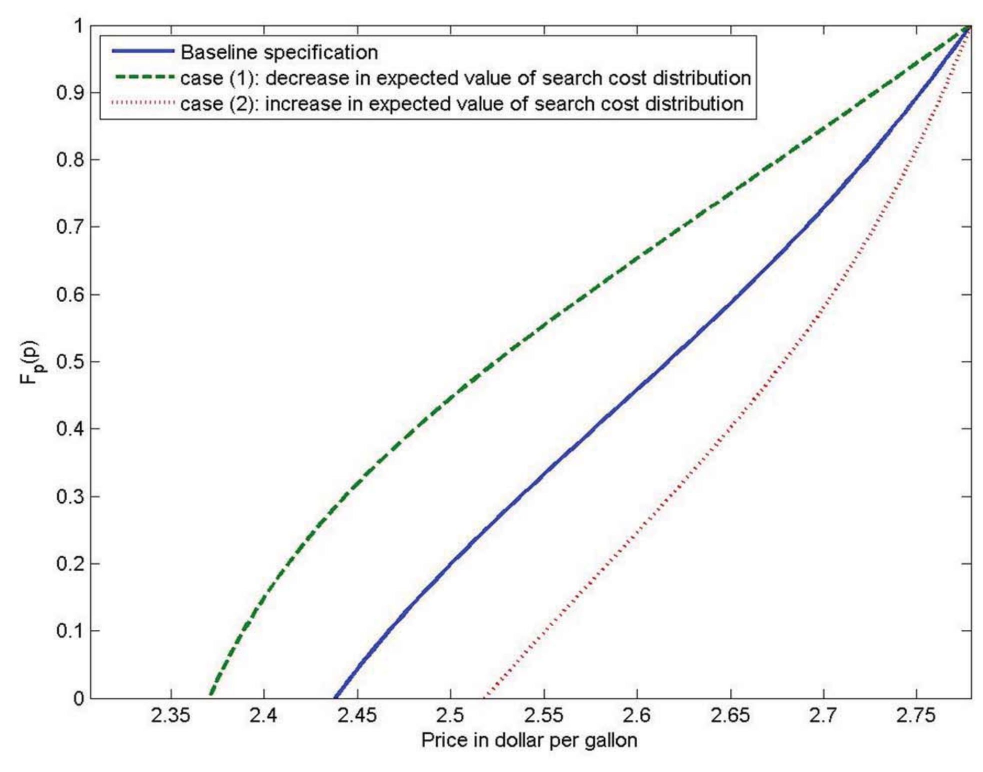


Figure A3a

Simulated price cdf with 5 stations, 20% change in standard deviation, and 10% decrease in the expected value of search cost CDF

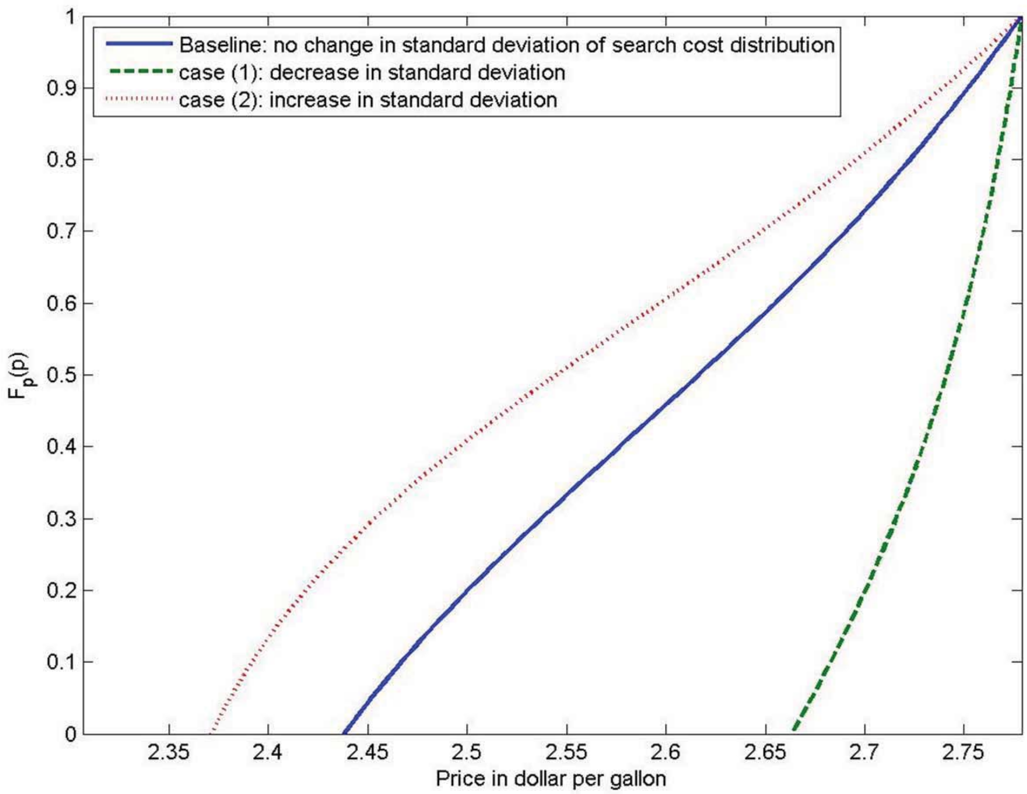


Figure A3b

Simulated price cdf with 5 stations, 22% change in standard deviation, and 10% decrease in the expected value of search cost CDF

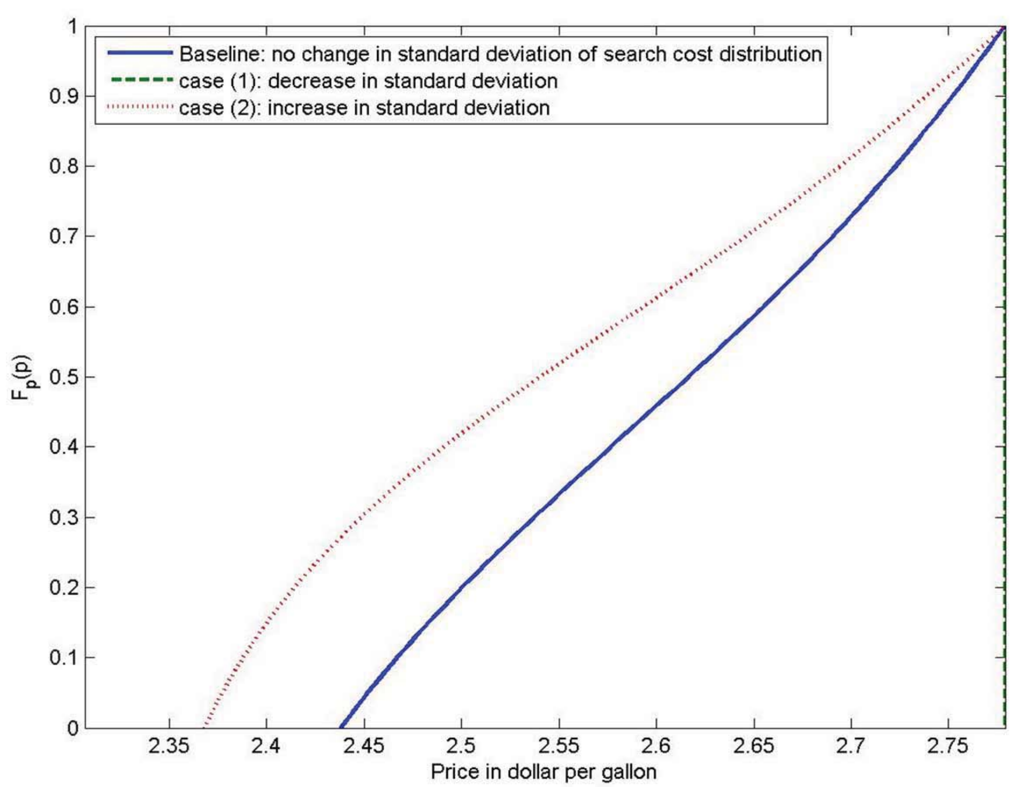


Table A1

Summary Statistics across Isolated Geographical Markets

	Mean	Std dev	Minimum	Maximum
Mean household income ($)	62,270	24,700	24,328	222,764
Years of education	12.523	1.204	8.640	16.071
Age	39.035	5.407	26.489	63.419
Distance among stations (miles)	0.416	0.332	0.002	1.470
Standard Deviation of Income	47,420	12,515	18,428	117,873

Note: The data source is the 2006-2010 American Community Survey. The unit of observation is a single-census isolated market; there are 354 observations.

Table A2

Price Dispersion Regression Estimates

Dispersion measure	Sample range				Standard deviation			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Constant	0.483	0.414	0.326	0.228	0.114	0.114	0.043	0.043
	0.070	0.077	0.257	0.261	0.024	0.026	0.083	0.084
Mean income	1.370	1.620			0.432	0.430		
	0.557	0.568			0.182	0.185		
Mean years of education	-0.020	-0.017			-0.004	-0.004		
	0.008	0.008			0.003	0.003		
Mean age	0.000	0.000			0.000	0.000		
	0.001	0.001			0.000	0.000		
Mean distance among stations	0.001	-0.005			-0.008	-0.008		
	0.016	0.016			0.005	0.005		
Standard deviation of income	-0.910	-1.380			-0.351	-0.347		
	1.120	1.140			0.347	0.358		
Number of Firms		0.011		0.010		0.000		0.000
		0.004		0.004		0.001		0.001
Log of mean income			0.132	0.153			0.043	0.043
			0.040	0.04			0.013	0.013
Log of mean years of education			-0.256	-0.233			-0.067	-0.067
			0.101	0.103			0.034	0.034
Log of mean age			-0.028	-0.013			-0.001	-0.001
			0.054	0.054			0.016	0.016
Log of mean distance among stations			0.007	0.004			0.000	0.000
			0.004	0.004			0.001	0.002
Log of standard deviation of income			-0.071	-0.097			-0.026	-0.026
			0.053	0.054			0.015	0.016
Number of observations	354	354	354	354	354	354	354	354

Note: Parameter estimates and standard errors are in the upper and lower row of each variable, respectively. Income is standardized to $100,000.

Table A3
The Effect of Change in Search Costs on Equilibrium Price Distribution: SOSD

	Baseline	(1) 15% decrease	(2) 15% increase	(3) 20% decrease	(4) 20% increase
Minimum price	2.438	0.195	-0.050	0.341	-0.061
Maximum price	2.779	0.000	0.000	0.000	0.000
Expected price (Ep)	2.613	0.106	-0.040	0.166	-0.049
Expected price paid	2.573	0.142	-0.062	0.206	-0.079
people with 10%tile search costs	2.492	0.203	-0.055	0.287	-0.068
people with 25%tile search costs	2.522	0.197	-0.073	0.257	-0.098
people with 50%tile search costs	2.613	0.106	-0.110	0.166	-0.122
people with 75%tile search costs	2.613	0.106	-0.040	0.166	-0.049
Sample range (p_{max} - p_{min})	0.341	-0.195	0.050	-0.341	0.061
Standard deviation of price	0.105	-0.062	0.018	-0.105	0.023
Expected search costs	0.287	0.000	0.000	0.000	0.000
Expected paid search costs	0.017	-0.014	0.005	-0.017	0.006
people with 10%tile search costs	0.039	-0.020	-0.020	-0.039	-0.024
people with 25%tile search costs	0.052	-0.052	-0.008	-0.052	-0.005
people with 50%tile search costs	0	0.000	0.051	0.000	0.044
people with 75%tile search costs	0	0.000	0.000	0.000	0.000
Expected total expenditure	2.590	0.128	-0.057	0.189	-0.072
people with 10%tile search costs	2.531	0.184	-0.075	0.248	-0.092
people with 25%tile search costs	2.575	0.144	-0.082	0.204	-0.103
people with 50%tile search costs	2.613	0.106	-0.059	0.166	-0.078
people with 75%tile search costs	2.613	0.106	-0.040	0.166	-0.049
Average number of search	1.027	-0.774	0.484	-1.027	0.626
people with 10%tile search costs	**4**	**-3**	0	**-4**	0
people with 25%tile search costs	2	-2	1	-2	2
people with 50%tile search costs	0	0	1	0	1
people with 75%tile search costs	**0**	**0**	0	**0**	0
Average marginal cost	2.307	0.000	0.000	0.000	0.000
Expected profit margin	0.266	0.142	-0.062	0.206	-0.078
Proportion of people with i price quotes (q_i)					
q_1	0.564	0.304	-0.132	0.436	-0.167
q_2	0.154	-0.083	0.000	-0.154	-0.004
q_3	0.096	-0.065	0.015	-0.096	0.016
q_4	0.061	-0.045	0.018	-0.061	0.022
q_5	0.124	-0.106	0.100	-0.124	0.134
Marginal expected savings from searching $i+1$ versus i stations (Δ_i)					
Δ_1	0.060	-0.036	0.010	-0.060	0.012
Δ_2	0.031	-0.018	0.003	-0.031	0.004
Δ_3	0.018	-0.009	0.002	-0.018	0.002
Δ_4	0.012	-0.006	0.000	-0.012	0.000

Note: The number of stations is five. We assume the marginal costs are $2.307 per gallon. The number of simulated price observations is 100. Columns (1) through (4) measure the increase from the corresponding value in the baseline specification.

Table A4
Summary Statistics of Simulated Equilibrium Pices by Market Structure

# of stations	Minimum price	Expected price	Expected price paid	Sample Range	Standard deviation of prices	Expected search costs paid	Total expenditure	Gains from search
2	2.549740	2.639609	2.627892	0.229260	0.065354	0.005347	2.633239	0.089869
3	2.477898	2.615278	2.588151	0.301102	0.092603	0.011918	2.600070	0.137380
4	2.451537	**2.612354**	2.577110	0.327463	0.101622	0.015448	2.592558	0.160816
5	2.438109	2.612645	2.573076	0.340891	0.105213	0.017396	2.590472	0.174536
6	2.430114	2.613401	2.571410	0.348886	0.106802	0.018524	2.589934	0.183287
7	2.424906	2.614084	2.570673	0.354094	0.107555	0.019206	**2.589879**	0.189178
8	2.421313	2.614610	2.570336	0.357687	0.107928	0.019632	2.589968	0.193298
9	2.418730	2.614996	2.570179	0.360270	0.108118	0.019907	2.590086	0.196265
10	2.416819	2.615274	2.570108	0.362181	0.108218	0.020087	2.590196	0.198455
11	2.415371	2.615475	2.570077	0.363629	0.108270	0.020208	2.590285	0.200104
12	2.414253	2.615620	2.570067	0.364747	0.108298	0.020292	2.590359	0.201367
13	2.413377	2.615726	**2.570064**	0.365623	0.108313	0.020352	2.590416	0.202350
14	2.412683	2.615804	2.570068	0.366317	0.108320	0.020394	2.590461	0.203121
15	2.412125	2.615863	2.570073	0.366875	0.108323	0.020424	2.590497	0.203737
16	2.411674	2.615906	2.570079	0.367326	0.108324	0.020446	2.590524	0.204232
17	2.411304	2.615940	2.570084	0.367696	**0.108325**	0.020462	2.590546	0.204636
18	2.411000	2.615965	2.570089	0.368000	**0.108324**	0.020474	2.590563	0.204965
19	2.410747	2.615985	2.570092	0.368253	**0.108325**	0.020484	2.590576	0.205238
20	2.410536	2.616000	2.570095	0.368464	0.108324	0.020491	2.590587	0.205464
21	2.410359	2.616012	2.570098	0.368641	0.108324	0.020497	2.590595	0.205653
22	2.410210	2.616019	2.570097	0.368790	0.108324	0.020501	2.590599	0.205809
23	2.410082	2.616026	2.570099	0.368918	0.108323	0.020505	2.590604	0.205944
24	2.409975	2.616031	2.570100	0.369025	0.108323	0.020507	2.590608	0.206056
25	2.409882	2.616036	2.570101	0.369118	0.108323	0.020510	2.590611	0.206153
26	2.409803	2.616039	2.570102	0.369197	0.108323	0.020511	2.590613	0.206237
27	2.409734	2.616042	2.570103	0.369266	0.108323	0.020513	2.590616	0.206308
28	2.409674	2.616045	2.570104	0.369326	0.108323	0.020514	2.590617	0.206370
29	2.409623	2.616047	2.570104	0.369377	0.108322	0.020515	2.590619	0.206424
30	2.409578	2.616048	2.570105	0.369422	0.108322	0.020515	2.590621	0.206470

Note: The unit is dollar per gallon.