

Gasoline Price Spikes and Regional Gasoline Content Regulations: A Structural Approach.

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Abstract

This paper studies the degree to which gasoline price spikes in California, Illinois and Wisconsin over 1995 to 2001 can be explained by regulatory differentiation - gasoline sold in California, Illinois and Wisconsin is chemically different than gasoline sold in other locations as a result of local regulation supplementary to the Clean Air Act Amendments of 1990. I specify a structural model based on the production optimization problem of refiners and estimate wholesale prices for jet fuel, diesel and four blends of gasoline in each geographic market. I then simulate a counterfactual in which gasoline in the three states meets federal requirements. Comparing the results from the counterfactual to the initial model, allows me to distinguish the degree to which prices spikes in these markets are the result of regulatory differentiation, rather than geographic heterogeneity. I estimate that 72, 92 and 91 percent of price spikes created by refinery fires in California, Illinois and Wisconsin could be mitigated by compatibility with federal RFG standards. Moreover, I also quantify the effect of two other factors thought to increase gasoline prices, (i) changes in refinery ownership and (ii) limited expansion of domestic refining capacity.

1 Introduction

Gasoline prices garner tremendous attention from regulators, legislators and consumers. One motivation for recent interest is that gasoline prices in different parts of the country often rise and fall substantially relative to one another. For example, the average retail price of gasoline in Chicago rose from \$1.61 to \$2.15 a gallon from May 1, 2000 to June 20, 2000. By July 24, the gasoline price in Chicago had dropped to \$1.49.¹ In contrast, the retail price in Houston,

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¹Final Report of the Federal Trade Commission on the Midwest Price Spikes, March 21, 2001; EIA retail gasoline price series

a city connected to Chicago by low-cost pipelines, rose from 1.48 to 1.59 and then fell to \$1.57 over the same period.

This paper studies the degree to which similar price spikes in California, Illinois and Wisconsin over 1995 to 2001 can be explained by regulatory differentiation - gasoline sold in California, Illinois and Wisconsin is chemically different than gasoline sold in other locations as a result of local regulation.² This paper quantifies the price effect of local gasoline content regulations in these three states. In addition, I quantify the effect of two other structural changes in the refining industry concurrent with the introduction of content regulations: (1) changes in refinery ownership related to mergers and divestitures over the study period, and (2) increasing utilization of domestic refining capacity. Moreover, this paper distinguishes the effect of regulatory differentiation created by state-level gasoline content regulations from the effect of geographic differentiation arising from transportation costs. Identifying the relationship between each form of differentiation has policy implications beyond gasoline pricing. To the extent that two jurisdictions are geographically heterogeneous, inconsistent regulation across the two will have little incremental effect. If transportation or travel costs between the two jurisdictions are low, though, regulatory differentiation may have a substantial effect.

To quantify the effect of the regulations in California, Illinois and Wisconsin, I specify a structural model of the refining industry based on the production optimization problem faced by individual refineries, allowing for unobservable cost, conduct and elasticity parameters. I estimate unobservable the unobservable parameters of the model numerically. Using the point estimates, I then simulate prices of wholesale gasoline in Illinois, Wisconsin and California as if the states used gasoline compatible with federal standards. This approach controls for transportation costs, refinery capacity constraints, and changes in refinery ownership. Using a self-constructed data set of refinery fires, explosions and other unexpected outages, I identify months with and without unanticipated local supply shocks. Comparing simulated prices in months with and without local refinery outages, I separately identify persistent effects of these regulations, such as additional production costs, from the dynamic effects of these regulations, arising from constraints limiting the ability to move gasoline between geographic markets in response to shocks. I also simulate counterfactuals controlling for refinery consolidation and declining reserve refining capacity. These simulations estimate the effect of changes in refinery ownership and domestic capacity constraints on wholesale gasoline prices.

Section 2 discusses the relevant economic and policy literature. Section 3 provides a back-

²Figure 1 graphs average monthly wholesale gasoline prices in California, Illinois and Texas. Figure 2 graphs the differential between each and the West Texas Intermediate Crude Spot price.

ground on content regulations and the refining industry, focusing in particular on why regulation of gasoline content and refinery outages effect wholesale gasoline prices and the relationship between the effects. Section 4 details the data used and section 5 presents a model of gasoline refining and discusses estimation and fit of the model. In Section 6, I specify counterfactuals and simulate the effect of the content regulations on regional wholesale gasoline price volatility. In addition, I also simulate alterative counterfactuals and test the robustness of the results to both modelling assumptions and the coefficients of the estimated structural parameters. Section 7 concludes.

2 Previous Literature

A number of academic papers, along with policy studies by the FTC, EPA, Senate Subcommittee on Investigations and state commissions, qualitatively analyze structural changes in regional gasoline markets contributing to large changes in regional gasoline prices.³ In general, these studies identify three structural changes in the gasoline markets that increase the frequency and magnitude of regional price spikes: (1) inconsistent gasoline content regulations across different geographic regions, (2) increasing domestic refinery utilization rates, and (3) industry consolidation within the oil industry. Focusing on specific incidents, previous qualitative studies identify incident-specific factors, including refinery outages, transportation constraints, reductions in product inventories, or transition costs associated with meeting new environmental regulations.

A few papers estimate wholesale and retail price effects of gasoline content regulations. These papers exploit cross-state or inter-temporal variation in regulation to estimate the effect of regulations on gasoline prices. Using a similar approach to previous research of other state-level regulatory policies, including divorcement regulation (Vita, 2000), self-service bans (Vandegrift and Bisti, 2001 and Johnson and Romeo, 2000), and sales-below-cost laws (Anderson and Johnson, 1999), Chouinard and Perloff (2002) and Chakravorty and Nauges (2005) estimate state-level retail and wholesale prices as a function of content regulations, along with other cost and demand shifters. More recently, Brown, Hastings, Mansur and Villas-Boas (2006) study the effects of regulation at the city-level, by pairing regulated and unregulated markets and employing a differences-in-differences approach. Despite differences in their methodologies, the studies find content regulations are associated with an increase in wholesale and retail gasoline prices of 3-6 cents per gallon.

³See for instance, Bulow, Creswell, Fischer and Taylor (2003) and “Gasoline Prices - How Are They Really Set?” (2002)

This paper departs from the reduced-form approach used in previous studies in favor of a structural approach similar to that used in Considine and Heo (2002). Considine and Heo specifies a structural models based on the production optimization problem facing refineries, determining production of not only gasoline, but also jet fuel, distillate and other petroleum products. Unlike these papers, which aggregate individual refiner behavior up to national prices and inventories, this paper optimizes the production decisions for individual refineries choosing quantities of products at the state-product level. I model the production choice of individual refineries incorporating refinery supply adjustment costs associated with rapid changes in refinery production identified in Borenstein and Shepard (2000). Explicitly modelling the production decisions of refiners allows me to control for factors that affect regional price levels and volatility, but are difficult to incorporate in a reduced-form approach, including refinery production constraints, changes in refinery ownership, transportation costs and substitutability of different refined products.

This paper identifies the extent to which regulatory heterogeneity and geographic differentiation separately contribute to differentiating the wholesale gasoline markets of California, Illinois and Wisconsin from that of other areas required to use special gasoline blends. Although different in approach, Pinske, Slade and Brett (2002) assess a similar question. Pinske, Slade and Brett use a semiparametric model to identify the geographic limits of domestic wholesale gasoline markets. While their approach does not rely on industry-specific structural assumptions, the structure I impose on my model allows for the simulation of several counterfactuals.

3 Industry Overview

3.1 Petroleum Basics

The petroleum industry is vertically organized into six steps: (i) Crude extraction and transportation to refineries (ii) refining of crude oil, (iii) Transportation of refined products by pipeline or barge to regional terminals, (iv) Storage and wholesale sale at regional terminals, (v) Transportation by truck to retail stations and (vi) Retail sale.

I focus on the production decision of refineries. Refineries heat crude oil and separates it into different parts or “streams” of intermediate products. The refiner then blends the streams together into end products such as gasoline, jet fuel and diesel.⁴ Due to the relative price

⁴End-products include everything from propane, gasoline and diesel fuel to industrial fuel oil and residuum for road tar. These products vary along many dimensions, including boiling point, energy content, and octane number. Light products, including gasoline, jet fuel, kerosene and diesel fuel, command a price premium relative to heavy

premium associated with gasoline, jet fuel and diesel, refiners maximize production of these light products subject to capacity constraints of refinery production units. Refiners trade off production between different light products in response to relative prices.

Refiners contract for crude oil several months in advance. The characteristics of the crude oil and the set of processing units at a particular refinery bound the set of end-products a particular refinery can produce. After the choice of crude oil is made, a refiner is constrained in the set of end products they can produce. Although a refiner is able to adjust the mix of refined products to a limited extent by changing the operation of the refinery, changes at this point are small relative to those made by refiners through the choice of crude oil. Thus, during a three to six week production run, when the choice of crude is effectively fixed, refiners have limited flexibility in the set of products they produce, while over time they have considerably more flexibility.⁵

Domestic refineries produce the vast majority of domestically-consumed light products, accounting for approximately ninety percent of gasoline, jet fuel and diesel consumption in 2001.⁶ Over fifty percent of domestic refining capacity is located in Texas, Louisiana and California.⁷ Remaining domestic refining capacity is sited near specific end markets (e.g. New York City, Philadelphia or Chicago) or other sources of crude oil (e.g. Wyoming). To meet regional demand, the East Coast, upper Midwest and occasionally West Coast import gasoline from Gulf Coast refineries. To supply these non-local markets, refiners in the Gulf ship petroleum products by barge or pipeline to regional wholesale terminals located near most metropolitan areas.⁸ Figure 3 maps the location and size of domestic refineries as well as product movements by barge or pipeline between areas.

Wholesale terminals serve as a point of sale for industrial and wholesale customers. Terminals also carry limited inventories, typically storing sufficient gasoline and other refined products to serve 2 weeks of local demand. From the terminal, gasoline is sold to retail stations either at the Dealer Tank Wagon (DTW) price or the Rack price, depending on whether or not the terminal operator provides truck transportation from the terminal to the retail station. Since transportation by truck is substantially more expensive than transportation by barge or pipeline,

products, such as fuel oil and coke.

⁵See Borenstein and Shepard (2001) and Muehlegger (2002) for discussions of supply adjustment costs in crude oil refining.

⁶Although international imports vary significantly by region, even in the area with the greatest product imports, the East Coast, imports accounted for 22, 21 and 23 percent of gasoline, jet fuel and diesel consumption.

⁷As of January 1, 2002, total domestic atmospheric distillation capacity was 17.6 million barrels per day - 25, 16 and 12 percent of this capacity was located in Texas, Louisiana and California respectively. Distillation is the first step in the refining process, where the refinery heats and separates crude oil based on boiling point.

⁸Gulf Coast refineries produced roughly 57 and 16 percent of wholesale gasoline consumed in PADD 1 (East Coast) and PADD 2 (Midwest), respectively, in 2001.

wholesale terminals are located near most metropolitan areas.

Aside from the introduction of gasoline content regulations, two structural changes in the petroleum industry affect refinery operation during the study period. Through mergers and divestitures, a number of large refineries changed ownership in the late 1990's.⁹ Although refinery divestitures required by the FTC prevented large increases in concentration indices, local changes in ownership may change refinery competition and production. In addition, domestic refining capacity has increased at a lower rate than demand for refined products since the early 1980's. In 1981, annual refinery production was 68 percent of refinery capacity.¹⁰ Due to closures of old refineries, increasing demand and limited capacity investment at existing sites over the past twenty years, current utilization of refining capacity exceeds 95 percent. Over the study period, refinery capacity constraints play a larger role over time.

3.2 Gasoline Content Regulations

In 1990, the the Clean Air Act Amendment mandated federal content criteria for gasoline in regions failing to meet EPA limits for ozone and carbon monoxide pollution. The amendment mandated three broad regional classes of gasoline: conventional, oxygenated and reformulated gasoline (RFG), designing oxygenated gasoline to reduce carbon emissions and RFG to limit ground-level ozone pollution.¹¹ Oxygenated gasoline contains a higher oxygen content than conventional gasoline reducing CO emissions in cold weather. Reformulated gasoline places limits on volatility, reducing the propensity of gasoline to evaporate and lowering ozone emissions.¹² Subsequent to the federal regulation, many states chose to enact supplementary regulations, either by voluntarily adopting the federal requirements or by mandating more strict regulations.¹³ As a result of state-level regulation, fifteen distinct gasoline blends were sold domestically in 2001. Figure 4 maps geographic boundaries of federal RFG and oxygenated programs as well as the geographic scope of state and local content regulations supplementing both federal programs.

During the study period, California, Illinois and Wisconsin imposed the most strict supplementary standards for gasoline relative to the standards of federal RFG. Standards for California

⁹Large horizontal mergers in the petroleum industry include British Petroleum and Amoco in 1998, Exxon and Mobil in 1999 and BP/Amoco and Arco in 2000.

¹⁰See Dazzo, N., Lidderdale, T., and N. Masterson, "U.S. Refining Capacity Utilization," Energy Information Administration, Petroleum Supply Monthly

¹¹See Muehlegger(2002) for a summary of state and federal gasoline content regulations.

¹²Ground-level ozone increase with temperature, as evaporative emissions increase, and also increases as a function of sunlight. Hence, ozone emissions rise in summer, in warm climates. Alternatively, carbon emissions increase with incomplete combustion associated with starting a cold engine, and are more of a problem in cold climates during the winter.

¹³Demand from regions opting-in to the federal RFG program accounts for approximately one-third of RFG demand.

Air Resource Board (CARB) gasoline limit the proportion of gasoline derived from particular intermediate streams and require gasoline to meet a sulfur cap. RFG sold in Illinois and Wisconsin meets identical volatility and oxygen content standard to federal RFG, but Illinois and Wisconsin enacted tax incentives such that local refiners meet the oxygen content requirement with ethanol. Ethanol's volatility is high relative to other oxygenates, such as MTBE, and as a result, refiners must create a very low volatility blendstock to mix with ethanol to meet the volatility requirement of federal RFG.

Although firms could opt to sell federal RFG in Chicago, they would forfeit tax benefits for MTBE-RFG, as well as for other gasoline mixed with the MTBE-RFG at the wholesale terminal. As a result, gasoline meeting federal RFG requirements is not sold in areas requiring CARB gasoline or ethanol-blended RFG. It is also important to note that not only does federal RFG fail to meet the content specifications of these two blends of gasoline, but CARB gasoline and ethanol-blended RFG are mutually incompatible.

I focus specifically regulatory differentiation of CARB, ethanol-blended RFG and federal RFG. Unlike oxygenated gasoline, these blends require refinery-level production adjustments and thus are completely incompatible after leaving the refinery. RFG.¹⁴ Oxygenated gasoline, on the other hand, may be met by increasing the oxygen content post-production.

3.3 Regional Price Volatility and Refinery Outages

The primary goal of this paper is to study the effect of regulatory differentiation of gasoline due to the introduction of supplementary state-level content regulations. In particular, this paper examines the extent to which content regulations in Illinois, Wisconsin and California contribute to gasoline price spikes resulting local supply shocks, in the form of fires, explosions and other unexpected outages at refineries.¹⁵

Regulatory differentiation of gasoline in California, Illinois and Wisconsin has three distinct price effects. First, CARB gasoline and ethanol-blended RFG are more costly to refine than conventional gasoline. Second, additional refining costs associated with state-specific content regulations might change the set of refiners who product a particular blend of gasoline. Finally, incompatible blends of gasoline constrain the response of refiners and marketers facing supply and demand shocks. The first two effects are persistent and would increase average gasoline

¹⁴Oxygenated gasoline can be met by additives which increase the oxygen content, and do not necessitate a change at the refinery level.

¹⁵Pipeline outages, which are not explicitly modelled in this paper, can act in a similar manner to supply shocks. Examples include the Pacific pipeline outage affecting Phoenix, AZ in August 2003 and the Colonial pipeline outage affecting the East Coast following Hurricane Katrina.

prices. The third only affects prices in the event of an unexpected supply or demand shock. Moreover, whether or not regulatory differentiation compounds the effect of supply and demand shocks is directly related to the degree of geographic differentiation across regions. For example, little gasoline meeting federal reformulated gasoline (RFG) standards is sold in the Midwest. Even if gasoline in Illinois and Milwaukee were compatible with federal RFG, transportation costs from locations producing federal RFG might be sufficient to limit shipments from other RFG-producing areas in response to a local shock in the Chicago gasoline market. In this case, the transportation costs rather than the regulatory differentiation contribute to the price effect resulting from a unexpected shock. If, on the other hand, transportation costs to Illinois and Milwaukee from other markets using federal RFG are relatively low, regulatory differentiation may compound the effect of a refinery outage.

4 Data

I collect two sets of data: (i) market-level prices and quantities, and (ii) refinery-level data influencing production decisions, such as oil prices, transportation costs and refinery outages.

The price and quantity data, from the Energy Information Administration (EIA) Petroleum Marketing Monthly, consist of monthly observations of wholesale price and quantity for the three major light petroleum products, gasoline, No.2 distillate (home heating oil and diesel fuel) and jet fuel. I use seven years of monthly observations at the state-formulation level, beginning Jan 1995 and ending with Dec 2001, after the Midwest and California price spikes of 2000 and 2001. A sample observation would be the wholesale price and quantity of federal RFG sold in Massachusetts in August 2000.¹⁶ Prices are average monthly “rack” price net of taxes for each state-formulation combination. The “rack” price is the wholesale price paid at the terminal and does not include any transportation costs from the terminal to the individual stations.¹⁷ For diesel and jet fuel, I use regional average monthly prices net of taxes of product sold for resale in each of eight petroleum area defense districts PADDs.¹⁸ Volumes for all products are prime supplier volumes defined as sales by wholesale marketers to retailers. To verify that prime supplier volumes are representative of wholesale gasoline volumes, I compare the EIA

¹⁶Ideally, the relevant market for wholesale gasoline would be at the terminal-formulation level. While state-level data does not bias the estimate of persistent effects of content regulation, it would lead to a conservative estimate of the effect of content regulation on price spikes if within-state transportation costs are sufficient to limit arbitrage between terminals within the same state.

¹⁷A shortcoming of the EIA data is that it does not differentiate between branded rack sales (eg. sales of Chevron gasoline) and unbranded rack sales.

¹⁸Roughly corresponding to the Northeast (1a), Mid-atlantic (1b), South-east (1c), Midwest (2), Gulf Coast (3), Rocky Mountains (4) and West Coast (5).

prime supplier gasoline volumes to state-reported monthly wholesale gasoline sales reported to the Federal Highway Administration.¹⁹

Although sales of CARB gasoline or ethanol-blended reformulated gasoline are not explicitly identified in the EIA data, both gasoline blends meet federal-RFG standards and are reported as such in the dataset. Since, no other gasoline blends in California, Illinois and Wisconsin meet federal RFG standards, I attribute all reported RFG sales in these states as either a sale of CARB gasoline or ethanol-blended RFG. I also aggregate conventional and oxygenated gasoline, since oxygenated gasoline is effectively undifferentiated from conventional gasoline at the refinery.

Thus, the structural model focuses on six light petroleum products, four of which are distinct blends of gasoline: (i) conventional gasoline, (ii) federal-mandate reformulated gasoline, (iii) ethanol-blended RFG, (iv) CARB gasoline, (v) jet fuel or kerosene, and (vi) diesel fuel or number two distillate fuel. My panel of market-level data consists of 6198 observations by month for sixty two state-formulations of gasoline, eight regional markets for jet fuel and eight regional markets for diesel fuel.²⁰

To simulate refinery production, I construct several refinery-specific variables covering (i) ownership and capacity of refineries, (ii) crude oil and transportation costs, (iii) refinery outage information, and (iv) petroleum product imports. I construct a comprehensive dataset of refinery ownership, closures and capacity over the study period from the EIA Petroleum Supply Annual and annual surveys conducted by the EIA of petroleum capacity at domestic refineries. While the annual surveys include the capacity of various production units at refineries, they do not explicitly define production capacity of gasoline, diesel and jet fuel at these refineries. I use a function of distillation and cracking capacity to calculate the production limit of light products at these refineries, based on crude oil assays which specify the mix of light products derivable from West Texas Intermediate at a simple (distillation only) refinery.²¹ Of the 173 domestic refineries operating at some point during the study period, I consider the subset of 117 refineries

¹⁹Although FHA data only report wholesale gasoline sales aggregated across federal formulation standards, I similarly aggregated EIA data for purposes of comparison. Aside from several instances of reporting or recording error in the FHA data, same-state same-month observations from the EIA data and the FHA data were, on average, within three percent of each other.

²⁰Sixty two gasoline markets are the result of some states having multiple formulations over the study period. For example, outside of the Milwaukee area, Wisconsin stations sell conventional gasoline. From January 1, 1995 until December 31, 1995, Milwaukee stations sold federal RFG while from January 1, 1996 on, Milwaukee stations sold ethanol-oxygenated RFG.

²¹Specifically, my calculation of light-product production capacity at these refineries is equal to forty percent of atmospheric distillation capacity added to the sum of thermal cracking capacity, catalytic cracking capacity and hydrocracking capacity. Although this is a rough measure of capacity, as crude choice affects production limits, individuals knowledgeable about refining consider this a reasonable approximation of light product capacity.

located in the contiguous US with light product production capacity exceeding eight hundred thousand gallons per day. This subset of refiners contains over ninety-five percent of estimated domestic light product capacity.²²

Crude oil costs for refineries are monthly average purchase prices of crude oil tracked by the EIA, adjusted for transportation. For refineries located in the Midwest or East Coast, I use the spot price of West Texas Intermediate at Cushing, OK, adjusted for pipeline transportation costs from Cushing to the refinery location. For refineries in Wyoming, Montana and Utah, I use a crude spot price for Wyoming Sour, and for refineries on the West Coast, I use an average spot price for Alaskan North Shore crude and California Offshore crude, all of which I adjust for transportation costs.²³

Transportation costs for petroleum products by pipelines, barges and trucks are estimates presented before the Federal Trade Commission of 2, 4.5 and 30 cents per gallon per thousand miles of transportation.²⁴ I identify each refinery's ability to serve each of the 78 markets described above using several sources. Maps of refineries and petroleum product pipelines determine pipeline access of each refinery. In addition, since pipelines are unidirectional, I use these maps to determine the markets each refinery is able to serve by pipeline. Access to barge transportation is determined either by proximity to water or access to pipelines serving water-proximate storage terminals. Transportation costs for each refinery-state combination are then calculated as the least cost method of serving the state from the refinery. For example, a refinery in Texas with access to barges is assumed to serve Nevada markets by barging product from Texas to California and then shipping that product by pipeline from California to Nevada. While I do not explicitly model pipeline constraints in this paper, omitting pipeline constraints would lead to a conservative estimate of the effect of content regulation on price volatility.

Imports of petroleum products are small relative to domestic production - hence, in the structural model, I take imports to be exogenous.²⁵ The EIA tracks monthly imports by petroleum district of a variety of finished petroleum products, including gasoline by federal-formulation standard. Conventional gasoline imports are assumed to be the sum of oxygenated imports and other gasoline imports. Jet fuel imports are assumed to be sum of jet fuel and aviation

²²Many smaller refineries produce specialized petroleum products for industrial use and do not actively produce gasoline, jet fuel and distillate. As a result, although these refineries account for approximately five percent of light-product capacity, they account for a smaller proportion of light product production.

²³Although different spot prices are used, crude spot prices in California, Alaska and Wyoming closely correlate with the WTI spot price at Cushing, OK.

²⁴See Colonial Pipeline presentation to the FTC. These values are consistent with estimates of transportation costs from the EIA's 2003 California Gasoline Price Study.

²⁵Imports of gasoline, jet fuel and diesel fuel were 10, 10 and 9 percent of domestic consumption in 2001.

gasoline imports. Reformulated gasoline and distillate fuel oil are taken as reported. Since the imports of motor gasoline are reported by PADD and not by state, I proportionately distribute imports to states within each PADD based on same-month consumption of either conventional or reformulated gasoline.

The supply shocks I exploit are unexpected refinery outages due to fires, explosions, lightning or other unexpected events at refineries. I identify unexpected outages by searching news, government and industry sources reporting events in the petroleum refining industry. Sources for information on outages include regional and national newspapers, SEC filings made by publicly-traded refiners, and incident reports by the US Chemical Safety Board, EPA and OSHA. I identify a total of 121 incidents, forty-five of which necessitated the shutdown of one or more processing units at the 117 refineries in my subsample from January 1995 to December 2001. For each of these incidents, I identify the processing unit or units involved, the duration of the outage, and estimate the effect of the outage on light-product production. Table 1 lists the unexpected outages I identify through news, regulatory and industry sources, along with the outage date, repair date and outage severity.

5 Structural Model of Supply Shocks

I consider a three step game in which refiners choose quantities of light petroleum products to maximize expected profits subject to changing information about refinery outages. Consistent with pre-production planning, in the first step, refineries commit to quantities of light petroleum products without knowing outages. In the second step, outages are realized and observed by all refineries. In the final step, refineries allocate production across different geographic areas in response to the outage. Thus, a refinery choosing to produce federal RFG, but not CARB gasoline, can redistribute federal RFG from one market to another in response to an outage, but cannot, in the short term, produce CARB gasoline instead.

In the first step, refineries have knowledge of all supply and demand variables with the exception of unexpected outages occurring in the current period. That is, prior to choosing initial production at time t , the inverse residual demand curve, $p_{jt}(\cdot)$, in each geographic-product market $j \in \{1, 2, \dots, J\}$ and the cost functions for all refineries are common knowledge. For each domestic refinery, $i \in \{1, 2, \dots, I\}$, let q_{ijt} be the initial choice of quantity in market j at time t , \bar{q}_{it} denote the total production capacity of all light petroleum products, $c(q_{i1}, q_{i2}, \dots, q_{iJ})$ be the refinery production cost function and t_{ij} denote the transportation costs from refinery i to market j .

Refiners choose quantities of each petroleum product to maximize the expectation, with respect to all possible refinery outages $\omega \in \Omega$, of own-refinery profits plus a portion of other refinery profits, α .²⁶ The objective function for a refiner owning refineries $\tilde{I} \subset \{1, 2, \dots, I\}$ is given by

$$U = E\left(\sum_{i \in \tilde{I}} \Pi_{it}\right) + \alpha E\left(\sum_{i' \notin \tilde{I}} \Pi_{i't}\right), \quad (1)$$

subject to refinery capacity and non-negativity constraints

$$q_{i1} + q_{i2} + \dots + q_{iJ} \leq \bar{q}_i \quad (2)$$

$$q_{ij} \geq 0 \quad (3)$$

for all $i \in \tilde{I}$ and all j where Π_{it} is again

$$\Pi_{it} = \sum_j \tilde{q}_{ijt}(p_j(\cdot)) - \sum_j \tilde{q}_{ijt}t_{ij} - c(\tilde{q}_{i1t}, \tilde{q}_{i2t}, \dots, \tilde{q}_{iJt}). \quad (4)$$

In the second step, refinery outages and severity are realized and fully observed by all refineries. If production at a refinery with initial production exceeding post-outage refinery capacity is curtailed by an outage at time t , production is scaled back evenly across all products.

In the third step, refiners allocate production across geographic markets response to the realization of outages $\omega \in \Omega$. Consistent with limited refinery operational flexibility during a production run, refineries can redistribute production across geographic markets, but cannot adjust the mix of petroleum they produce in step three. Let $\{J_1, J_2, \dots, J_n\}$ be a proper partition of markets $\{1, 2, \dots, J\}$ by product content, where all markets sharing a given set of content regulations belong to one element of $\{J_1, J_2, \dots, J_n\}$.²⁷ In the third step, a refiner owning a set of refineries $\tilde{I} \subset \{1, 2, \dots, I\}$ again chooses quantities $\{\tilde{q}_{ijt}\}$ for $i \in \tilde{I}$ to maximize an objective function consisting of own-refinery profits plus a portion of other refinery profits given by

$$U = \sum_{i \in \tilde{I}} \Pi_{it} + \alpha \sum_{i' \notin \tilde{I}} \Pi_{i't} \quad (5)$$

where Π_{it} is given by

²⁶See Cyert and DeGroot (1973). In this formulation, the interpretation of α is the weight an individual refiner places on the profits of refineries it does not own. A value of $\alpha = 1$ is consistent with joint profit maximization by all refiners while a value of $\alpha = 0$ implies entirely own-profit maximization.

²⁷For example, J_1 could denote conventional gasoline markets, J_2 reformulated gasoline markets, J_3 jet fuel markets, and J_4 CARB gasoline.

$$\Pi_{it} = \sum_j \tilde{q}_{ijt}(p_j(\cdot)) - \sum_j \tilde{q}_{ijt}t_{ij} - c(\tilde{q}_{i1t}, \tilde{q}_{i2t}, \dots, \tilde{q}_{iJt}). \quad (6)$$

subject to non-negativity constraints and binding product-level capacity constraints

$$\tilde{q}_{ij} \geq 0 \text{ for all } j \in J \quad (7)$$

$$\sum_{j \in J_1} \tilde{q}_{ij} = \sum_{j \in J_1} q_{ij} \quad (8)$$

$$\sum_{j \in J_2} \tilde{q}_{ij} = \sum_{j \in J_2} q_{ij}$$

...

$$\sum_{j \in J_n} \tilde{q}_{ij} = \sum_{j \in J_n} q_{ij}$$

Suppressing the time subscript, initial choice of production of refinery i for market j satisfies the first order condition

$$q_{ij} \frac{\partial p_j}{\partial q_{ij}} + \sum_{k \in \bar{I}/i} q_{kj} \frac{\partial p_j}{\partial q_{ij}} + \alpha \sum_{k \notin \bar{I}} q_{kj} \frac{\partial p_j}{\partial q_{ij}} + p_j - t_{ij} - \frac{\partial c_i}{\partial q_{ij}} + \lambda_i + \mu_{ij} = 0$$

where λ_i denotes the shadow cost of production capacity at refinery i and μ_{ij} denotes the non-negativity constraint. In months with outages, the final choice of production of refinery i for market j satisfies

$$q_{ij} \frac{\partial p_j}{\partial q_{ij}} + \sum_{k \in \bar{I}/i} q_{kj} \frac{\partial p_j}{\partial q_{ij}} + \alpha \sum_{k \notin \bar{I}} q_{kj} \frac{\partial p_j}{\partial q_{ij}} + p_j - t_{ij} - \frac{\partial c_i}{\partial q_{ij}} + \hat{\lambda}_{ij} + \mu_{ij} = 0,$$

where $\hat{\lambda}_{ij}$ denotes the shadow cost of the production constraint of refinery i to increase production of a petroleum product compatible with product j . Alternatively, expressing the FOC as a lerner-style index, the quantities of all I refineries must jointly satisfy the set of I first order conditions for market j , given by

$$\frac{p_j - t_{ij} - \frac{\partial c_i}{\partial q_{ij}} + \lambda_i + \mu_{ij}}{p_j} = \frac{1}{\epsilon_{ij}} + \sum_{k \in \bar{I}/i} \frac{1}{\epsilon_{kj}} + \alpha \sum_{k \notin \bar{I}} \frac{1}{\epsilon_{kj}},$$

where ϵ_{ij} denotes elasticity of the residual demand curve faced by refinery i in market j at quantity q_{ij} .

I make functional form assumptions for the cost and demand functions, $c(q_{i1}, q_{i2}, \dots, q_{iJ})$ and $p_{jt}(\cdot)$. I assume refinery production costs are additively separable and that the marginal

cost of refinery i to produce a fuel for market j at time t is

$$MC_{ijt} = \beta_1 * OilPrice_{it} + \beta_2 * Log(DC_{it}) + \beta_3 * CONV_j + \beta_4 * RFG_j + \beta_5 * ERFG_j + \beta_6 * CARB_j + \beta_7 * JF_j + \beta_8 * DIST_j \quad (9)$$

where $OilPrice_{it}$ is the delivered oil price at refinery i , $Log(DC_{it})$ is the log of atmospheric distillation capacity of refinery i , and $CONV_j$, RFG_j , $ERFG_j$, $CARB_j$, JF_j and $DIST_j$ are dummy variables corresponding to conventional gasoline, reformulated gasoline, ethanol-blended RFG, CARB gasoline, jet fuel and distillate.²⁸ The choice of functional form allows for differential production costs by product, economies of scale in refinery distillation capacity and region-specific crude prices, incorporating both the price of local crude streams and transportation to the refinery.

I introduce a stochastic error term into the inverse demand curve for each market, $p_{jt}(\cdot)$, common to all refiners and realized after refiners choose quantities in each market. Take $\epsilon_{jt} \sim N(0, \sigma_j^2)$ to be an additive stochastic shock to the inverse demand curve for market j from the previous section,

$$p_{jt}(q) = p_{jt}^A + \left(\frac{-p_{jt}^A}{e q_{jt}^A} \right) (q_{jt} - q_{jt}^A) + \epsilon_{jt}. \quad (10)$$

I assume that ϵ_{jt} is independently distributed across geographic areas. Intuitively, this source of error is akin to a common market shock to a population's propensity to drive, unobservable to refiners, such as weather conditions. This specification is equivalent to a first-order Taylor approximation of an isoelastic demand curve, $q_{jt}(p_{jt}) = \frac{\gamma}{e} p_{jt}^e$, taken at the observed price and quantity in market j at time t .

5.1 Estimation

Absent the functional form specifications for the cost and demand functions, the model defines a deterministic correspondence, $f : (X, \theta, \epsilon) \rightarrow Y$, between factors influencing refinery supply decisions, such as content regulations, input and transportation costs collectively denoted (X), the vector of unobserved cost, conduct and elasticity parameters (θ), the vector of error terms ϵ , and market-level prices and quantities (Y).²⁹ That is, f maps a given state space and values for

²⁸Although other products exist, including residuum, residual oil and other light products, gasoline, distillate and jet fuel constitute the vast majority of light products produced at refineries. In addition, the properties of each are similar enough that similar intermediate streams are used for each.

²⁹The set of unobservables, denoted θ , consists of the eight cost parameters $\{\beta_1, \beta_2, \dots, \beta_8\}$, the conduct parameter α and demand elasticity parameter e .

unobservable parameters to all market equilibria that are solutions to the refinery optimization problem. Given the functional form assumptions, the set of FOCs simplifies to a full-rank linear problem. Thus, the functional form assumptions provide a sufficient condition for f to be a function and for a unique solution to the optimization problem.

Linearity of the refiner FOC's allows me to separably express Y_{jt} as a function of the predicted output, $f(X_t, \theta)$, and the stochastic error ϵ_{jt} .

$$Y_{jt} = f(X_t, \theta) + \epsilon_{jt}, \epsilon_{jt} \sim N(0, \sigma_j^2).$$

I numerically search for the NLLS set of parameters, that is,

$$\hat{\theta} = \underset{\theta}{\operatorname{argmin}} ((f(X, \theta) - Y)'(f(X, \theta) - Y)).$$

I estimate $\hat{\theta}$ numerically, finding the vector of values for θ minimizing the squared error between $f(X, \theta)$ and Y via a steepest ascent search algorithm.³⁰ As part of my robustness checks, I test the sensitivity of my simulation results to variations in the NLLS parameter point estimates.

In addition, the expectation is taken with respect to the continuous state space of all possible refinery outages. In order to numerically solve for $f(X_t, \theta)$, I initially assume refiners place a zero prior probability on unexpected refinery outages. Treating the optimization in this way induces refineries to produce less CARB and ethanol-blended RFG than they otherwise would if they assumed an outage at a plant in California or Illinois were likely. As part of my sensitivity analyses, I verify the robustness of my simulations by allowing for refineries to place a positive prior probability on a discrete subspace of the continuum of all possible refinery outages. I find that this assumption does not change my conclusions. Although outages have a large local effect, the probability of an outage is low.³¹ When choosing production, refiners weigh the benefits of committing to incremental CARB or ethanol-RFG production in states of the world in which a local outage occurs in California, Illinois or Wisconsin, against the incremental production costs associated with manufacturing CARB or ethanol-RFG as well as the shadow-cost of capacity if the refinery is capacity constrained. As a result, assuming refiners place a zero probability prior on unexpected outages does not change refinery choice of production significantly. When

³⁰In this case, the steepest ascent search algorithm is computationally efficient relative to a method requiring computation of the second derivatives, such as Gauss-Newton. The seed point for the steepest ascent algorithm, $\alpha = .15, \beta_1 = 1, \beta_2 = -1, \beta_3 = 5, \beta_4 = 10, \beta_5 = 13, \beta_6 = 15, \beta_7 = 3, \beta_8 = 1$, is based on an initial simulation of PADD 5 only and ex-ante government estimates for production costs of different gasoline blends.

³¹Over the study period, news, industry and government sources document only forty-five production-lowering outages. The expected monthly percentage of total refinery capacity down due to an unexpected outage is 0.2 percent.

simulated, the magnitude of the effect is an order of magnitude less than the effect of the content regulations.

5.2 Point Estimates

Table 2 reports the point estimates for $\hat{\theta}$. The coefficient on log distillation capacity, β_1 , is less than 0, consistent with increasing returns to distillation capacity. The coefficient on crude cost, β_2 is below the ex ante prediction of 1. This suggests that the spot price overstates the price of crude oil processed at refineries, possibly due to long term contracts whose prices vary less than domestic spot prices. Cost parameters corresponding to differential production costs for different product blends are similar to government and industry estimates. The incremental production costs relative to conventional gasoline for federal RFG and CARB gasoline are within EPA and CARB estimates of four to eight cents and five to fifteen cents respectively.

The competition coefficient and elasticity estimates are similar to expectations as well. The point estimate for α is 0.03 and is not statistically different from 0. This result is consistent with refiners making their production decisions based purely on self-interest and that persistent tacit collusion amongst refiners is not prevalent, consistent with the conclusions of academic and non-academic studies.³²

The estimate of short-run gasoline demand elasticity is consistent with both the meta-analysis presented in Espey(1998) and recent estimates in Considine (2001). Espey finds the mean and median of 363 estimates of short run gasoline demand to be -0.26 and -0.23, respectively. The model point estimate of the short run elasticity, -0.337, is statistically indistinguishable from the median and mean of the sample collected in Espey.³³

5.3 Model Fit

I use two metrics to assess how well the model predicts actual prices. By product and geographic market, I compare the first and second moments of the simulated and actual prices, to assess whether, in aggregate, the model accurately predicts differences in wholesale prices across products and geographic markets. I then compare the average predicted and actual price change over the previous month in months and states with local refinery outages.

Table 3a and 3b list descriptive statistics for actual and estimated prices across different

³²See, in particular, Bulow et al. (2003) and FTC Midwest Price Spike Investigation (2001). This approach, though, cannot rule out infrequent collusion by refiners.

³³As part of my robustness checks, I perform specific sensitivity tests to verify that my simulations estimates are robust to the assumption of more inelastic demand.

petroleum products and different PADD regions. First and second moments simulated wholesale prices are similar across blends and regions to those of actual prices. Across geographic regions, all estimates from the structural and reduced-form models are within four percent of the actual means. The structural model overpredicts mean product price in PADD 3 (Gulf Coast) and PADD 1a (New England) by 2.8 cpg and 1.6 cpg, and underpredicts prices in PADD 4 (Rocky Mountains) and PADD 1b (Mid-Atlantic) by 1.5 and 1.2 cpg. Mean estimates for the PADD 2 (Midwest) and PADD 5 (West Coast) are within 0.5 cpg of the actual means. Mean prices, by formulation, estimated by the model are near actual means as well. The largest over- or under-estimation of mean price is that of CARB gasoline, overestimated by six percent.

Maximum simulated prices are lower than the maximum actual wholesale prices from 1995 through 2001. The largest deviation exists for ethanol-blended RFG where the difference between estimated and actual maximum prices is 30 cpg during the Midwest gasoline price spike in Spring 2000. While several refinery outages occurred in Spring 2000, these do not sufficiently explain the large change in the price ethanol-blended RFG.³⁴ During this period, ethanol-blended RFG was first required to meet more strict federal Phase II guidelines. Initially, refiners had difficulty meeting Phase II emission guidelines while continuing to use ethanol as an oxygenate. These idiosyncratic transition difficulties contributed to high gasoline prices, but are not explicitly modelled, leading to predicted prices that are substantially below actual prices for ethanol-blended RFG during May 2000.

I assess the degree to which the model accurately captures the effect of refinery outages by first-difference the simulated and actual wholesale prices in months with unexpected local outages. The model predicts wholesale price responses to local outages well. The average change in wholesale ethanol-blended RFG prices in months with a local unexpected outage is 9.91 and 9.90 cents per gallon in Illinois and Wisconsin, which is close to the actual mean change of 10.08 and 9.71 cents per gallon respectively. For CARB gasoline, simulated average change in wholesale prices in months with unexpected outages of California refineries is 5.91 cents per gallon, relative to an actual mean change of 6.65 cents per gallon.

6 Simulation Results

Using the point estimates of the cost, conduct and elasticity parameters, I simulate wholesale prices under several counterfactuals to quantify the effects of content regulation, changes in

³⁴Contributing factors to the Spring 2000 price spike are qualitatively discussed in Bulow et al (2003) and FTC (2001).

ownership and declining reserve refining capacity.

6.1 Effects of Gasoline Content Regulation

I estimate the effect of CARB gasoline and ethanol-blended RFG on regional price levels and the extent to these local content regulations contribute to price spikes caused by refinery outages. To quantify the effect of these regulations, I simulate counterfactual prices for each of my 78 markets as if the content regulations in California, Illinois and Wisconsin simply met federal RFG standards.³⁵

To quantify the effect of regulatory differentiation in California, Illinois and Wisconsin, I compare the predicted prices with the existing regulations (base case) to the predicted prices in the counterfactual, where California, Illinois and Wisconsin use federal-RFG. I calculate the difference in average prices between the base case and counterfactual for California, Illinois and Wisconsin conditional on whether or not a local refinery outage occurred. The calculated difference in average prices and standard errors are tabulated in Table 6.

Conditioning on outage allows separation of the persistent effects of regulatory differentiation, such as increased production costs or changes to local competition, from the dynamic effect of the constraints placed on refiners responding to supply shocks by regulatory differentiation. The average price differential (column 3, Table 6) between the base case and counterfactual in months without local outages identifies the persistent effects of regulatory differentiation. The incremental difference in months with local outages identifies the additional dynamic effects of incompatible gasoline regulations.³⁶

The point estimates of persistent effects on price of regulatory differentiation in California, Chicago and Milwaukee are 4.5, 3.0 and 2.9 cents per gallon. In other words, conditional on outage-free operation of all domestic refineries, expected wholesale price in California, Chicago and Milwaukee would be 4.5, 3.0 and 2.9 cents per gallon lower if areas used federal-RFG instead of CARB gasoline and ethanol-blended RFG. Conditional on a local refinery outage, regulatory differentiation in California, Illinois and Wisconsin raise wholesale gasoline prices an additional 4.8, 6.6 and 7.0 cents per gallon respectively.³⁷ This effect, incremental to the persistent effects of 4.5, 3.0 and 2.9 cents per gallon, captures the constraints local content regulations place

³⁵I hold all outages, changes in ownership, capacity additions, and input costs constant. The only difference between the base case and initial counterfactual is the gasoline formulation used in California, Illinois and Wisconsin.

³⁶For outages exceeding a month in duration, I only consider the first month of the outage. Refiners adjust production mix after the first month to account for the outage.

³⁷Substantial variation in the magnitude of local outages exists - the model predicts that the largest outages in California, Illinois and Wisconsin increase gasoline prices by 20-30 cents per gallon.

on refiners who would otherwise reallocate federal-RFG in response to shocks. These results suggest that reducing regulatory differentiation through compatibility with federal RFG would have a larger effect on gasoline prices when refinery outages occur in Illinois and Wisconsin than in California.

Two explanations for the larger incremental effect of regulatory differentiation and refinery outages in Illinois and Wisconsin are consistent with these results. The first is that transportation costs from the Gulf Coast to Illinois are less than the transportation costs from the Gulf Coast to California - That is, less geographic differentiation exists between Illinois and the Gulf Coast than between California and the Gulf Coast. Absent incompatible content regulations, lower transportation costs to Illinois would lead Gulf Coast refineries producing federal-RFG for the East coast to more fully compensate for a refinery outage in Illinois than for a refinery outage in California. A second explanation, though, is that local refinery outages realized in Illinois and Wisconsin were of greater magnitude than those in California. The magnitude of refinery outages create a bound to the potential benefits of compatibility with federal RFG, and thus, might partially explain the difference between the magnitude of the effects in the three states.

To distinguish between these two explanations, I estimate the magnitude of refinery outages in the three states, which provide an upper bound on the reallocation benefits arising from compatibility. If the latter explanation is valid, the refinery outages during the study period in Illinois and Wisconsin should have a proportionately larger effect on prices than refinery outages in California. I quantify the magnitude of the refinery outages by simulating prices in a counterfactual in which local content regulations exist but no refinery outages occur. I compare the average prices predicted in the counterfactual to those predicted in the base case. Table 5 provides the average difference between the predicted prices in the counterfactual and base case conditional and unconditional on outage, an estimate of the magnitude of refinery outages. The point estimates for the average magnitude of local refinery outages are 6.7, 7.3 and 7.7 cents per gallon for California, Chicago and Milwaukee respectively, although they cannot be distinguished statistically.

The estimates in Table 5 provide a metric by which to normalize the estimates of the effect of compatibility with federal RFG across the three states. Calculating the ratio of the effect of fuel incompatibility to the effect of the refinery outages gives an estimate of the proportion of the effect of local outages which could be mitigated if local content regulations met less stringent federal RFG standards. The proportion mitigated by compatibility with federal RFG

in California, Illinois and Wisconsin is 72, 91 and 92 percent respectively. That is, in California, of the 6.7 cent per gallon average simulated increase in price due to local outages, 4.8 cents of the increase (72 percent) would be avoided if CARB regulations were compatible with federal-RFG standards. Thus, although refinery outages were of greater magnitude in Chicago and Milwaukee than in California, fuel compatibility still has a larger effect on prices contingent on a local refinery outage, even after controlling for outage magnitude. These results imply that price volatility from local refinery outages could be substantially mitigated by content regulation compatible with federal RFG standards, especially in the case of Illinois and Wisconsin.

Differentiation in wholesale gasoline markets arises from both regulatory differentiation (ie. different content regulations) and geographic differentiation (ie. transportation costs). The initial counterfactual simulates prices in the three states removing the regulatory differentiation, but not geographic differentiation. The extent to which compatibility with federal RFG mitigates refinery outages depends on the geographic differentiation between the three wholesale markets and refiners producing federal RFG for other markets. Fuel compatibility only mitigates a supply shock if transportation costs from refiners producing RFG in other regions are sufficiently low. If gasoline sold in Chicago and Milwaukee met federal RFG standards, Gulf Coast refineries producing federal RFG for the East Coast could shift shipments to Chicago and Milwaukee via low cost pipelines in response to a refinery outage in Illinois. In contrast, these refineries, also the lowest cost non-local source of RFG for California, ship by barge to California, incurring higher transportation costs. The price differential between California and Texas must be greater to induce the same amount of reallocation of RFG in response to a supply shock. Thus, higher transportation costs imply less mitigation of an outage-based price spike of similar magnitude. This result indicates that virtually all of the differentiation for Chicago and Milwaukee ethanol-blended RFG is due to regulatory differentiation. In contrast, both regulatory and geographic differentiation contribute to price spikes in California.

6.2 Additional Counterfactuals

In addition to simulating the effect of incompatible content regulations, I also simulate two other counterfactuals. First, I estimate the effect of changes in refinery ownership over the 1995-2001 period on wholesale gasoline prices. Second, I simulate a counterfactual in which I increase the production capacity of all refineries, to estimate the effect of declining reserve refining capacity.

6.2.1 Changes in Refinery Concentration

I simulate prices, holding refinery ownership from January 1995 constant throughout the period. That is, I simulate prices as if no changes in refinery ownership occurred. All refinery retirements or capacity additions are kept identical to those actually observed. I first calculate the average simulated prices under the counterfactual by PADD region (Table 4a) and product formulation (Table 4b). Comparing the simulated prices for the counterfactual to the simulated prices for the base case estimates the effect of refinery consolidation on wholesale prices. Comparing the prices in Tables 4a and 4b, predicted mean wholesale prices by region are between 0.9 cpg and 1.3 cpg higher with actual refinery consolidation. Predicted prices for CARB gasoline are not statistically different with and without changes in ownership. Predicted prices for ethanol-blended RFG are 1.5 cpg greater under actual refinery consolidation than under the counterfactual holding asset ownership fixed.

I also estimate the effect of refinery ownership on gasoline price spikes caused by local refinery outages. In Table 7, I present the average price differential between the counterfactual and base case for CARB gasoline, Illinois RFG and Wisconsin RFG contingent and uncontingent on refinery outages. Conditioning on outage has little effect on the results for CARB gasoline. While the point difference between the predicted prices with and without changes in refinery ownership is larger conditional on an outage, it is still imprecisely estimated and not statistically different than zero. For Illinois and Wisconsin, though, changes in refinery ownership do lead to a significant 4 to 4.5 cpg increase in prices conditional on a outage than conditional on the absence of outages. This result suggests that changes in refinery ownership may affect the set of refineries in Illinois and Wisconsin which produce ethanol-blended RFG.

6.2.2 Declining Reserve Refining Capacity

I also simulate a counterfactual testing the effect of declining reserve refining capacity. That is, I estimate the price effect of capacity constraints on many of the largest domestic refineries. I specify three counterfactuals, increasing light product production capacity of all domestic refineries by 2.5%, 5% and 7.5%.³⁸ Allowing capacity to increase has two effects - it relaxes the binding capacity constraint at the most efficient refineries and relaxes the binding capacity constraint in gasoline-importing regions. Increasing refining capacity should reduce prices in all areas as production is shifted to more efficient refineries but should also reduce prices relatively

³⁸In the simulation, refinery cost functions are held constant, to control only for the effect of relaxing the capacity constraint on refineries. Outages are scaled proportionately with increases in capacity.

more in gasoline-importing regions. As above, Tables 4a and 4b present the descriptive statistics for the simulated counterfactual prices by geographic and product market and Table 8 presents the simulated price differential between the counterfactual and the base case, conditional and unconditional on refinery outages.

The results in Tables 4a and 4b are consistent with ex ante predictions. Increasing refinery capacity by five percent lowers prices in all geographic markets between 3.9 and 4.5 cents per gallon. In addition, the districts experiencing the largest price reductions are the Rocky Mountain states (PADD 4 - 4.5 cpg) and New England (PADD 1a - 4.3 cpg). Capacity-constrained geographic regions benefit from both reallocation of production to the most efficient refineries and the relaxation of the binding capacity constraint on local refineries. Areas with excess refining capacity only benefit from the former.

Increasing production capacity of all refineries by five percent does not effect substantively which refineries produce CARB or ethanol-blended RFG gasoline. Thus, the average price differentials reported in Table 8 contingent on a local outage and contingent on no outages are statistically indistinguishable.

6.3 Sensitivity Analyses

To test the robustness of the estimates in Section 8.1, I test the sensitivity of the simulated prices to the assumption that refiners place a zero probability prior on refinery outages and to changes in the estimated cost, conduct and elasticity parameters.

6.3.1 Forward-Looking Refinery Optimization

To test sensitivity of the results to the assumption that refiners place a zero prior probability on unexpected outages, I simulate a counterfactual in which each risk-neutral refiner places a common, positive prior on outages at each refinery.³⁹ For computational tractability, firms only consider the effects of single, refinery-wide outages. Firms choose production in step 1 to maximize expected profits and then are allowed to reallocate production after observing the realized set of outages.

Table 9a and 9b compare predicted prices when refiners incorporate a positive probability of outage to the predictions from the initial model. The mean predicted prices for ethanol-blended RFG and CARB gasoline are 0.45 cpg and 0.34 cpg lower when refinery optimization decisions incorporate outages than when they do not. Mean predicted prices for conventional gasoline,

³⁹I set the probability to be 0.0021, consistent with actual observed outages during the study period.

RFG, jet fuel and distillate are between 0.11 cpg lower to 0.07 cpg higher. This is consistent with ex ante expectations - outages have the greatest effect on CARB and ethanol-blended RFG prices. If refiners incorporate the probability of outages into their initial choice of production, refiners will increase production of CARB and ethanol-blended RFG relative to other products.

When compared to the effect of regulatory differentiation on prices, the effect of the modelling assumption is an order of magnitude less. While each refiner's priors of a refinery-wide outage somewhere in the system in a given month is approximately twenty-five percent, each refiner's priors of an outage at a specific refinery is much lower. Since the prior probability of a local refinery outage in Illinois, Wisconsin or California is relatively low, refiners rarely benefit from increasing production of CARB or ethanol-blended RFG above the level of production modelled in the base case.⁴⁰ Furthermore, capacity constraints prevent many refiners from increasing production of CARB or ethanol-blended RFG without decreasing production of another product. In choosing to produce more CARB or ethanol-blended RFG, capacity-constrained refineries weigh the benefits of incremental production in the event of a relevant local refinery outage against the incremental production cost of the special gasoline blend and the shadow cost of additional refining capacity.

6.3.2 Estimated Structural Parameters

In addition to testing the sensitivity of the simulation results to the assumption of profit maximization, I also test the sensitivity of the results to variation in the structural parameter estimates. I focus on the six unobserved parameters which have the largest effect on simulated CARB and ethanol-blended RFG prices: demand elasticity (ϵ), the competition coefficient (α), the coefficient on crude oil price (β_2), RFG production costs (β_3), ethanol-blended RFG production costs (β_4) and CARB production costs (β_5).⁴¹ In each of the sensitivity tests, I bound the coefficients at two standard deviations above and below the NLLS point estimates reported in Table 2.

The first sensitivity analyses test the robustness of the estimates to changes in the demand elasticity. The effect of content regulations contingent on a local outage is positively correlated with demand elasticity. If demand curves are less elastic, a supply shock of similar magnitude has a greater effect on prices. The estimated proportion of volatility from local outages mitigated by fuel compatibility is relatively close to the results from the NLLS minimizing parameter vector,

⁴⁰Common refinery priors for an outage in Illinois or Wisconsin is 0.015 and for an outage in California is 0.05.

⁴¹For brevity, tables with the results of the sensitivity analyses have been omitted from the text. Sensitivity results are available from the author.

69 and 73 percent for California, 90 to 95 percent for Illinois and 89 to 94 percent for Wisconsin.

The other sensitivity tests are consistent with expectations. Parameters affecting incremental production costs of regional content regulations tend to have the greatest effect on the average prices. differential between the base case and counterfactual simulations. Across the sensitivity tests, the effect of compatibility contingent on local outages varies from 8.5 to 11.0 for California, 7.8 to 11.7 for Illinois and 8.2 to 12.3 for Wisconsin. While the point estimates of the effect of content regulations contingent on a local outage vary by twenty percent, the proportion of the price volatility mitigated by compatibility with federal RFG is fairly robust across sensitivity tests. The degree to which compatibility with federal RFG mitigates local outages varies from 67 to 74 percent for California, 88 to 98 percent for Illinois and 90 to 99 percent for Wisconsin. Although the price effects of CARB and ethanol-blended RFG vary across sensitivity tests, the conclusion that compatibility with federal RFG has the potential to mitigate a significant proportion of the effect of local refinery outages, especially in Illinois and Wisconsin is robust.

7 Conclusion

In this paper, I use a structural model of refinery production to study how regional gasoline content regulations affect gasoline prices in California, Illinois and Wisconsin. Using a constructed dataset of refinery outages, I am able to separate the effect of the regulations on prices through increased production costs and the effect of the regulations on prices through fuel incompatibility. Point estimates for the effect of the former are 4.5, 3.0 and 2.9 cents per gallon in California, Illinois and Wisconsin. The effect of the latter, contingent on a local refinery outage, is estimated as 4.8, 6.6 and 7.1 cents in California, Illinois and Wisconsin. Controlling for the magnitude of local outages in these areas, I estimate that 72, 91 and 92 percent of price spike created by a local refinery outage could be mitigated by compatibility with federal reformulated gasoline. The sensitivity results in section 8 suggest that the conclusions are robust to changes in parameter estimates and to the assumptions of refiner's priors regarding the probability of unexpected outages. In particular, it seems that across the sensitivity tests, in all cases gasoline compatibility with federal RFG may play an important role in moderating price spikes from refinery outages in California, Illinois and Wisconsin.

In addition, I simulate several counterfactuals to estimate the effects on wholesale prices of changing refinery ownership over 1995 through 2001 and limited additions to domestic refining capacity. I find that changes in refinery ownership over the period increase prices by 1.4 to 1.5 cpg in Illinois and Wisconsin, but do not have a statistically significant effect on the price of

CARB gasoline. A five-percent increase in domestic refining capacity reduces prices 3.7 to 3.8 cents per gallon in Illinois and Wisconsin and 4.3 cents per gallon in California. Looking across PADD districts, I find that increasing refining capacity lowers prices most in regions which currently import petroleum products from other regions, namely the Rocky Mountain states (PADD 4) and the East Coast (PADD 1).

This study raises clear public policy implications. Back of the envelope calculations estimate the cost, through 2001, of content regulations incompatible with federal RFG standards in California, Illinois and Wisconsin at \$4.3 billion, \$670 million and \$160 million respectively relative to federal RFG. Since the motivation for these regulations is to reduce air pollution, it is important to assess whether CARB gasoline and ethanol-blended RFG constitute cost-effective methods for achieving this goal. To the extent that supplementary content regulations imposed by these states have little effect on mobile emissions, lower cost strategies may exist to reduce emissions in these states.

In addition, this paper suggests that differentiation created by incompatible regulation across neighboring jurisdictions plays an important role in how gasoline markets respond to supply shocks. The extent to which regulatory differentiation affects a particular market, though, depends on the degree of geographic differentiation which exists. Markets with little geographic heterogeneity, due to low transportation or travel costs, should expect regulatory differentiation to have large effects. Relatively geographically isolated markets, for which transportation or travel costs are high, should expect regulatory differentiation to have less of an effect.

References

- [1] Anderson, R., and R. Johnson, "Antitrust and Sales-Below-Cost Laws: The Case of Retail Gasoline," *Review of Industrial Organization*, v14, 1999, pp. 189-204.
- [2] Bacon, R., "Rockets and Feathers: The Asymmetric Speed of Adjustment of UK Retail Gasoline Prices to Cost Changes," *Energy Economics*, July 1991, pp. 211-218.
- [3] Blass, A., and D. Carlton, "The Choice of Organizational Form in Gasoline Retailing and the Cost of Laws that Limit that Choice," *Journal of Law and Economics*, v44, October 2001, pp. 511-524.
- [4] Borenstein, S., "Selling Costs and Switching Costs: Explaining Retail Gasoline Margins," *RAND Journal of Economics*, v22 n3, Autumn 1991, pp. 354-369.
- [5] Borenstein, S., J. Bushnell and M. Lewis "Market Power in California's Gasoline Market," *CSEM Working Paper 132*, May 2004.
- [6] Borenstein, S., C. Cameron and R. Gilbert, "Do Gasoline Prices Respond Asymmetrically to Crude Oil Price Changes?," *Quarterly Journal of Economics*, February 1997, pp. 305-339.
- [7] Borenstein, S., and A. Shepard, "Sticky Prices, Inventories, and Market Power in Wholesale Gasoline Markets," *UCEI POWER Working Paper*, August 2000.
- [8] Borenstein, S., and A. Shepard, "Dynamic Pricing in Retail Gasoline Markets," *RAND Journal of Economics*, v27 n3, Autumn 1996, pp. 429-451.
- [9] Brown, J., Hastings, J., Mansur, E., and S. Villas-Boas, "Reformulating Competition? Gasoline Content Regulation and Wholesale Gasoline Prices," *CUDARE Working Paper 1010*, 2006.
- [10] Bulow, J., Fischer J., Creswell, J., and C. Taylor, "U.S. Midwest Gasoline Pricing and the Spring 2000 Price Spike," *The Energy Journal*, v24 n3, 2003.
- [11] Chakravorty, U. and C. Nauges, "Clean Air Regulation and Heterogeneity in US Gasoline Markets," *working paper*, 2005.
- [12] Chouinard, H. and J. Perloff, "Gasoline Price Differences: Taxes, Pollution Regulations, Mergers, Market Power and Market Conditions," *CUDARE Working Paper 951*, 2002.
- [13] Considine, T., "Markup Pricing in Petroleum Refining: A Multiproduct Framework," *International Journal of Industrial Organization*, v19, 2001, pp. 1499-1526.
- [14] Considine, T., and E. Heo, "Price and Inventory Dynamics in Petroleum Product Markets," *Energy Economics*, v22, 2000, pp. 527-547.
- [15] Cyert, R. and M. DeGroot, "An Analysis of Cooperation and Learning in a Duopoly Context," *American Economic Review*, v63 n1, March 1973, pp. 24-37.
- [16] Dahl, C. and T. Sterner,, "Analyzing Gasoline Demand Elasticities: A Survey," *Energy Economics*, v13, 1991, pp. 203-210.
- [17] Davis, M. and J. Hamilton, "Why are Prices Sticky? The Dynamics of Wholesale Gasoline Prices," *NBER Working Paper 9741*, May 2003.
- [18] Energy Information Administration - Office of Oil and Gas, "Gasoline Type Proliferation and Price Volatility," Sept 2002.
- [19] Energy Information Administration - Office of Oil and Gas, "2003 California Gasoline Price Study: Preliminary Findings," May 2003.
- [20] Environmental Protection Agency - Office of Air Quality, "National Air Quality and Emissions Trends Report, 1999," March 2001, EPA 454/R-01-004.
- [21] Espey, M., "Gasoline Demand Revisited: An International Meta-Analysis of Elasticities," *Energy Economics*, v20, 1998, pp. 273-295.

- [22] Federal Trade Commission “Final Report - Midwest Price Spike Investigation,” March 29, 2001.
- [23] Greene, W., “Econometric Analysis: Fourth Edition,” Prentice Hall, 2000.
- [24] Geroski, P., A. Ulph and D Ulph, “A Model of the Crude Oil Market in which Market Conduct Varies,” *Economic Journal*, v97, 1987, pp. 77-86.
- [25] Hastings, J., “Vertical Relationships and Competition in Retail Gasoline Markets,” *mimeo*, 2003.
- [26] Hastings., J. and R. Gilbert, “Vertical Integration in Gasoline Supply: An Empirical Test of Raising Rivals’ Costs,” *UCEI POWER Working Paper*, PWP-084, March 2002.
- [27] Innes, R., “Regulating Automobile Pollution under Certainty, Competition and Imperfect Information,” *Journal of Environmental Economics and Management*, v31, 1996, pp. 219-239.
- [28] Johnson, R., “Search Costs, Lags and Prices at the Pump,” *Review of Industrial Organization*, v20, 2002, pp. 33-50.
- [29] Johnson, R., and J. Romeo, “The Impact of Self-Service Bans in the Retail Gasoline Market,” *The Review of Economics and Statistics*, v82 n4, November 2000, pp. 625-633.
- [30] Lidderdale, T., “Areas Participating in the Reformulated Gasoline Program,” *Energy Information Administration Short Term Energy Outlook*, July 1999.
- [31] Maples, R., *Petroleum Refining Process Economics*, Pennwell Books, Tulsa, OK, 1993.
- [32] Muehlegger, E., “The Role of Content Regulation on Pricing and Market Power in Regional Retail and Wholesale Gasoline Markets,” *MIT Center for Energy and Environmental Policy Research Working Paper*, WP-2002-08, November 2002.
- [33] Nicol, C., “Elasticities of Demand for Gasoline in Canada and the United States,” *Energy Economics*, v25, 2003, pp. 201-214.
- [34] Puller, S. and L. Greening, “Household Adjustment to Gasoline Price Change: An Analysis Using Nine Years of US Survey Data,” *Energy Economics*, v21, 1999, pp. 37-52.
- [35] Pinske, J., M. Slade, and C Brett, “Spatial Price Competition: A Semiparametric Approach,” *Econometrica*, v70(3), 2002, pp. 1111-1153.
- [36] Harrington, W., M. Walls, and V. McConnell, “Shifting Gears: New Directions for Cars and Clean Air,” *Resources for the Future Discussion Paper*, 94-26-REV, Feb 1995.
- [37] Slade, M., “Interfirm Rivalry in a Repeated Game: An Empirical Test of Tacit Collusion,” *Journal of Industrial Economics*, v35 n4, June 1987, pp. 499-516.
- [38] Simpson, J. and C. Taylor, “Michigan Gasoline Pricing and Marathon-Ashland and Ultramar Diamond Shamrock Transaction,” *Federal Trade Commission Working Paper 278*, July 2005.
- [39] US Senate Permanent Subcommittee on Investigations, “Gas Prices: How Are They Really Set?,” May 2, 2002.
- [40] Vandergrift, J. and J. Bisti, “The Economic Effects of New Jersey’s Self-Serve Operations Ban on Retail Gasoline Markets,” *Journal of Consumer Policy*, v24, 2001, pp. 63-81.
- [41] Vita, M., “Regulatory Restrictions on Vertical Integration and Control: The Competitive Impact of Gasoline Divorcement Policies,” *Journal of Regulatory Economics*, v18 n3, 2000, pp. 217-233.

**Figure 1: Average Monthly Prices for Crude Oil,
CARB gasoline, Illinois Ethanol-Blended RFG and Texas RFG
Jan 1995 - Dec 2003**

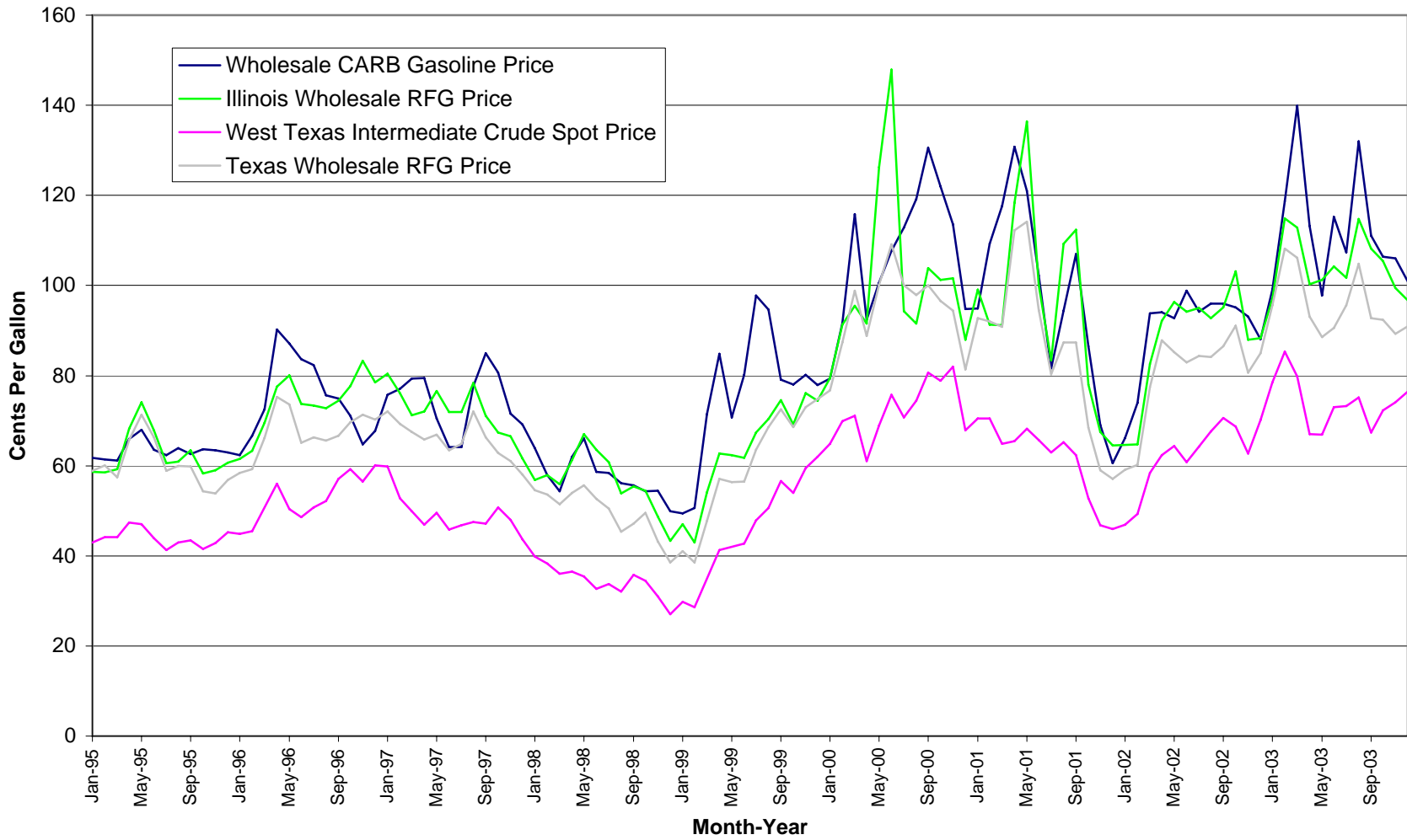


Figure 2: Gasoline Rack Price - WTI Spot Price Differential
Jan 1995 - Dec 2003

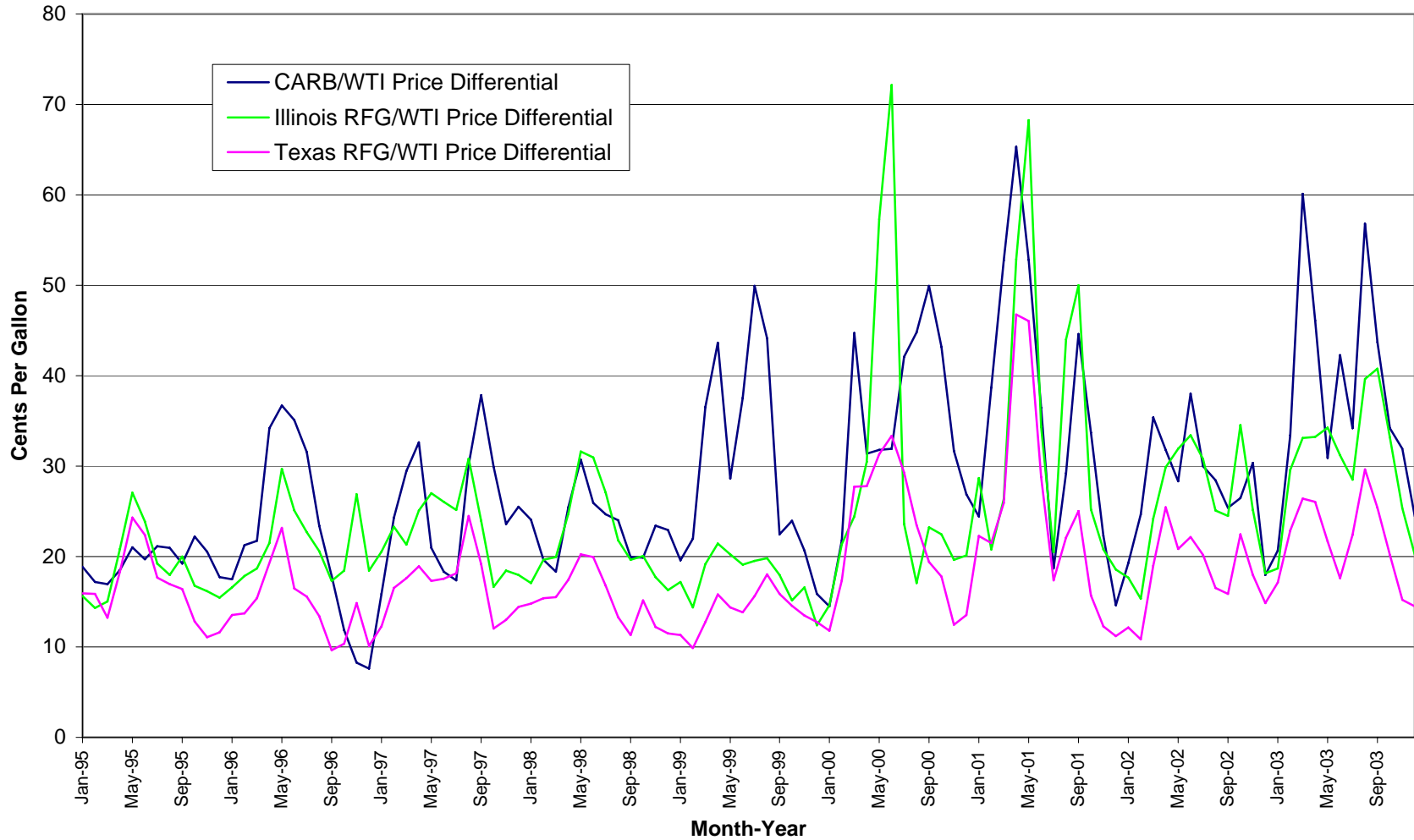
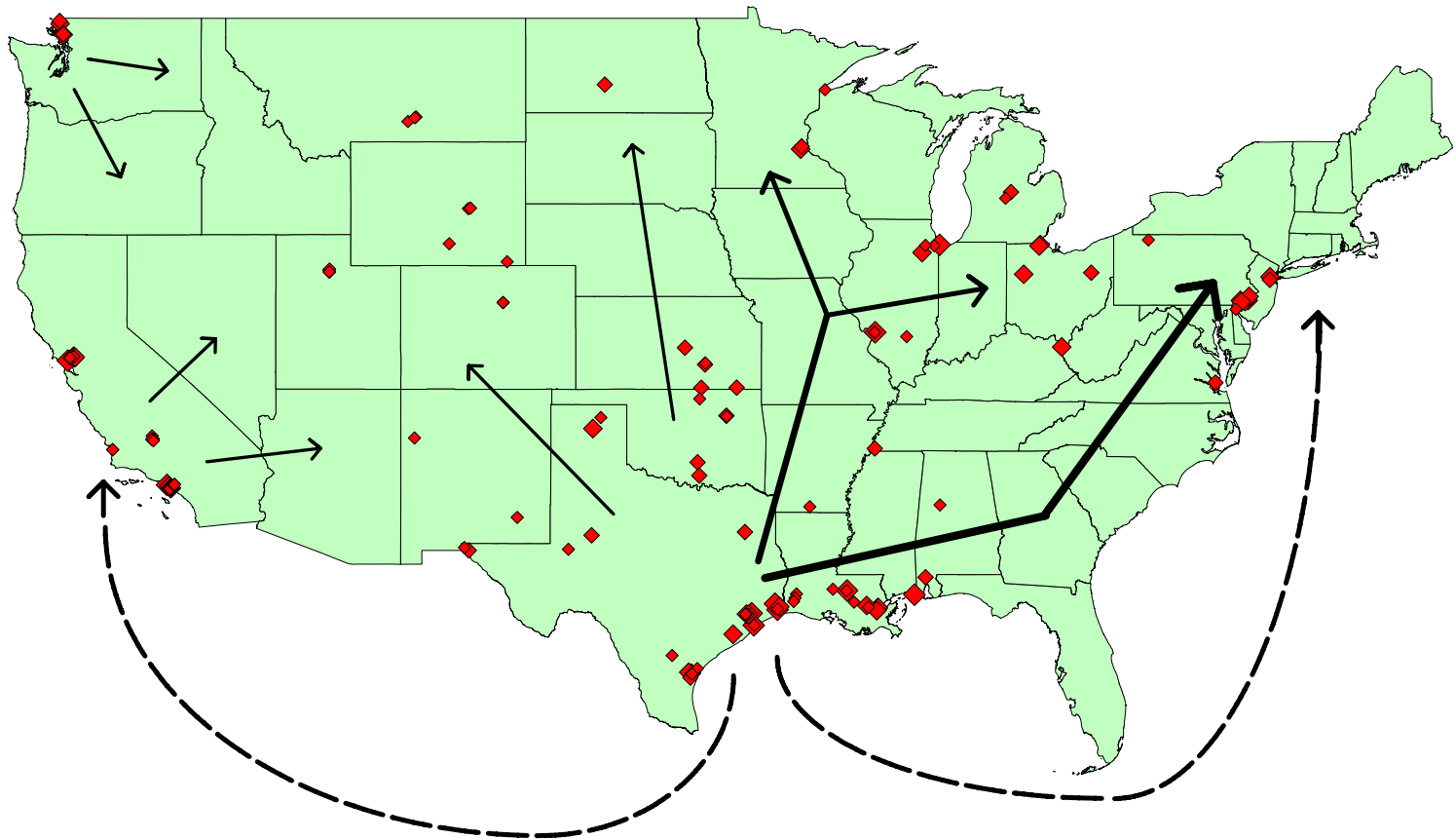


Figure 3: Oil Refineries and Refined Product Movements



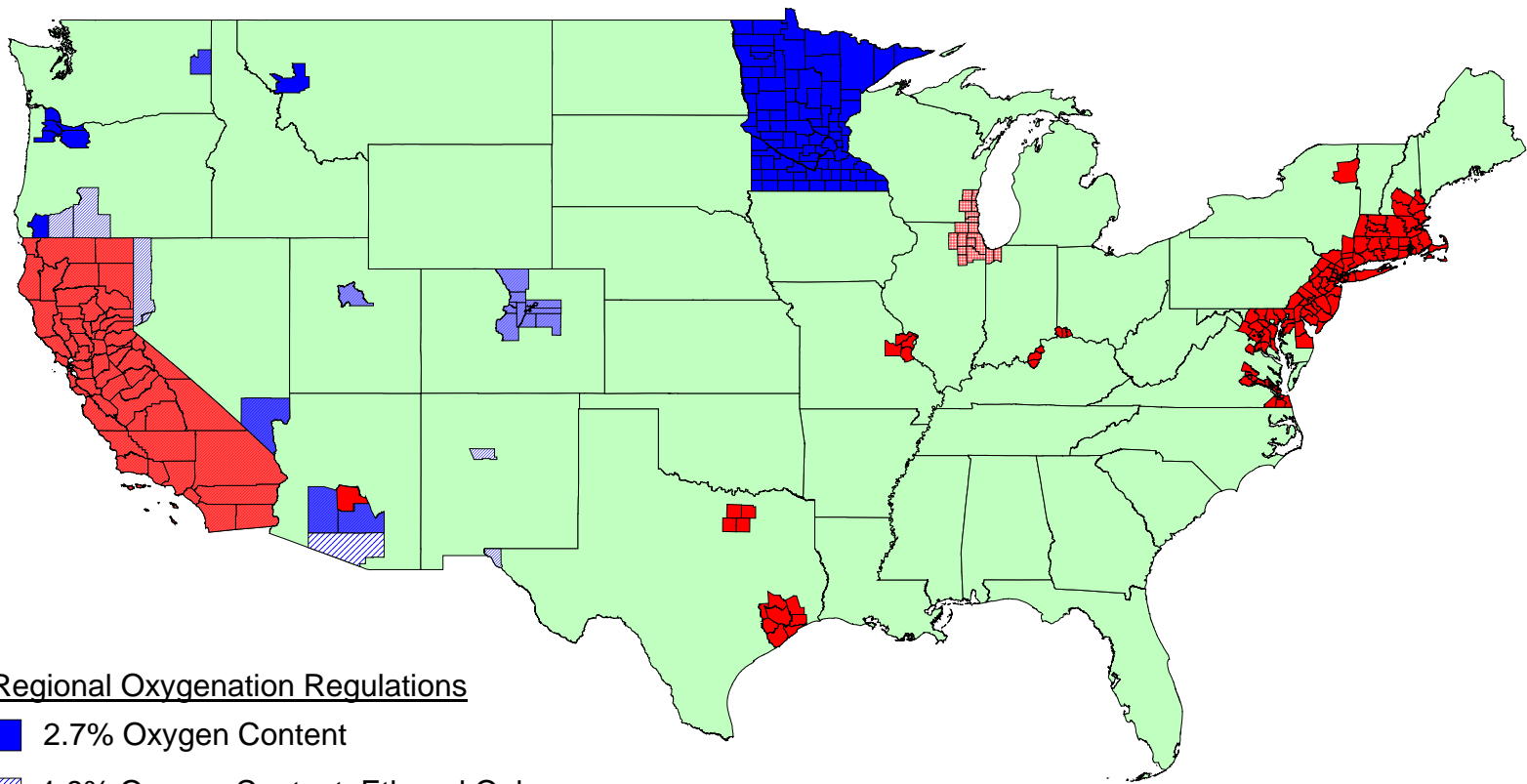
Refined Product Movements

- Pipeline
- - - Barge

Domestic Oil Refineries

- ◆ Less Than 50k bbls/day
- ◆ Between 50k and 100k bbls/day
- ◆ Between 100k and 250k bbls/day
- ◆ Over 250k bbls/day

Figure 4: Regional Gasoline Content Regulations



Regional Oxygenation Regulations

- 2.7% Oxygen Content
- 1.8% Oxygen Content, Ethanol Only
- 2.7% Oxygen Content, Ethanol Only
- 3.1% Oxygen Content, Ethanol Only
- 3.5% Oxygen Content, Ethanol Only

Regional RFG Regulations

- Federal Reformulated Gasoline
- CARB Gasoline
- Ethanol-Blended RFG

Note: Minnesota mandates year-round oxygenation. Other oxygenation mandates only affect winter gasoline content.

Table 1: Unexpected Refinery Outages Affecting Production of Light Products.

State	Refinery	Refiner	Outage Nature	Outage Date	Repair Date	Outage Severity	
						(000s/gals/day)	Sources
TEXAS	Pasadena	Crown Central Petro Group	Explosion prior to maintenance of distillation tower	23-Nov-01	21-Dec-01	4,200	c
LOUISIANA	Lake Charles	Citgo	Explosion and fire at hydrocracker unit	21-Sep-01	17-Oct-01	1,537	a, c
DELAWARE	Delaware City	Motiva	Maintenance at crude unit due to acid spill	20-Sep-01	10-Oct-01	7,014	c
OKLAHOMA	Ponca City	Conoco	Removal of 54kbbbl/day cat cracker from service	16-Aug-01	8-Sep-01	2,268	a
ILLINOIS	Lemont	PDV America/Citgo	Fire at Lemont Refinery crude distillation unit	14-Aug-01	25-Sep-01	7,014	a, b
TEXAS	Deer Park	deer park ltd	Fire closes facility for several days	8-Aug-01	11-Aug-01	13,461	a
DELAWARE	Delaware City	Motiva	Fire and acid spill	17-Jul-01	20-Sep-01	2,338	c
TEXAS	Three Rivers	Ultramar Diamond Shamrock	Fire and Explosion in alkylation unit	9-Jul-01	23-Jul-01	3,755	a, c
TEXAS	Port Arthur	Blackstone Group	Lightning strike necessitates maintenance of distillation tower	1-May-01	7/6/2001	840	a
UTAH	Woods Cross	Inland	Fire prompts water upgrade	4-Jul-01	4-Aug-01	437	a
LOUISIANA	Norco	Orion	Lightning strikes gasoline storage tank	7-Jun-01	10-Jun-01	3,255	a, b, c
CALIFORNIA	Los Angeles	BP	Fire at catalytic cracking unit	26-May-01	10-Jun-01	4,032	b
ALABAMA	Tuscoloosa	Hunt Refining	Major fire at refinery	13-May-01	15-May-01	1,092	a, b
ILLINOIS	Wood River	Tosco	Fire in pump of distillation unit.	28-Apr-01	22-May-01	5,282	a, b
CALIFORNIA	Benicia	ExxonMobil	Delayed restart to Benecia	1-Mar-01	1-Apr-01	5,670	a
ILLINOIS	Blue Island	Clark	Refinery upgrades.	1-Jan-01	1-Oct-01	3,041	a
PENNSYLVANIA	Philadelphia	Sunoco	Fire at distillation tower.	7-Sep-00	28-Sep-00	5,460	c, d
ILLINOIS	Robinson	Marathon Ashland	Fire at reformer and hydrocracker.	5-Aug-00	5-Sep-00	1,050	c
PENNSYLVANIA	Philadelphia	Sunoco	Catalyst release shuts down catalytic cracking unit	21-Jun-00	5-Jul-00	4,767	c
LOUISIANA	Norco	Orion	Explosion of diesel fuel.	10-Jun-00	24-Jun-00	3,612	a
TEXAS	Port Arthur	Blackstone Group	Unscheduled outage of distillation unit.	25-May-00	5-Jun-00	8,337	d
LOUISIANA	Shreveport	Pennzoil	Naphtha explosion.	18-Jan-00	2-Feb-00	1,281	a, b, d
OHIO	Toledo	Sunoco	Fire and small explosion near distillation tower.	28-Aug-99	11-Sep-99	3,028	b, d
ALABAMA	Tuscoloosa	Hunt Refining	Fire in processing facility.	18-Aug-99	31-Aug-99	1,092	a
CALIFORNIA	Richmond	Chevron	Fire at refinery.	10-Jul-99	15-Aug-99	5,040	a, d
TENNESSEE	Memphis	Williams	Fire at catalytic cracking unit	16-Jun-99	21-Jun-99	2,688	a
TEXAS	Corpus Christi	Coastal Corp	Fire at reformer.	14-May-99	14-Jun-99	630	a
INDIANA	Whiting	BP	Explosion from leaking jet fuel at catalytic cracker.	20-Apr-99	15-May-99	6,586	a
CALIFORNIA	Los Angeles	Arco	Failure of cogeneration plant halts operation.	27-Mar-99	29-Mar-99	10,731	a
CALIFORNIA	Richmond	Chevron	Fire and explosion in hydrocracking unit.	26-Mar-99	1-Mar-00	1,722	a, d
CALIFORNIA	Avon	Tosco	Fire and explosion at distillation tower.	23-Feb-99	1-Aug-99	6,897	a, c
ILLINOIS	Lemont	Citgo	Fire at distillation unit.	23-Feb-99	6-Mar-99	7,014	a
ARKANSAS	Smackover	Cross Petrol	Explosion at Naphtha tank.	13-Jan-99	10-Feb-99	235	a
LOUISIANA	Belle Chasse	BP	Fire at refinery.	2-Oct-98	5-Oct-98	9,862	a
OKLAHOMA	Ardmore	Ultramar Diamond Shamrock	Fire and power failure at distillation tower.	13-Jul-98	18-Sep-98	2,856	b, d
PENNSYLVANIA	Philadelphia	Sunoco	Power outage necessitates maintenance of catalytic cracker.	26-Jun-98	25-Jul-98	3,066	d
CALIFORNIA	Avon	Tosco	Explosion at hydrocracker.	22-Jan-97	24-Jan-97	2,688	a, d
NEW JERSEY	Bayway	Tosco	Unscheduled maintenance of catalytic cracker.	1-Jan-97	22-Jan-97	5,796	d
ILLINOIS	Blue Island	clark oil	Propane fire spurs damages electrical systems.	19-Oct-96	8-Nov-96	1,303	a, d
OHIO	toledo	BP	Fire at refinery.	15-Oct-96	23-Oct-96	5,880	a
MINNESOTA	Pine Bend	Koch	Lightning necessitates shutdown of distillation unit.	21-May-96	31-May-96	10,080	a
CALIFORNIA	Martinez	Shell	Explosion at hydrotreater.	1-Apr-96	22-Apr-96	3,173	a
COLORADO	Commerce City	TPI	Fire at refinery.	5-Feb-96	19-Feb-96	1,806	a
TEXAS	Texas City	Amoco	Explosion and fire at catalytic cracker at largest US refinery.	25-Jul-95	25-Aug-95	4,070	a

Sources:

- (a) Local News Sources
- (b) US Chemical Safety Board, Chemical Incident Report Center
- (c) Monthly Incident Reports from www.acusafe.com
- (d) SEC filings.

Table 2: Structural Parameter Estimates

Variable	Point Estimate	Standard Error
Demand Elasticity	0.337	0.151
Competition Coefficient	0.031	0.018
Cost Function Parameters		
Log (Distillation Capacity)	-0.867	0.01
Crude Oil Price	0.765	0.24
Conventional Gasoline Dummy	0.436	0.10
RFG Dummy	5.445	1.28
Ethanol-blended RFG Dummy	8.646	0.71
CARB Dummy	10.953	3.49
Jet Fuel Dummy	-1.322	1.12
No. 2 Distillate Dummy	-3.561	1.63
Pseudo R-squared	0.926	

Table 3a: Descriptive Statistics by PADD and Estimation Technique

	PADD Region						
	1a	1b	1c	2	3	4	5
Actual Prices							
Mean	69.56	68.82	66.74	70.35	66.12	74.84	74.91
Standard Deviation	16.67	16.95	16.36	18.28	16.61	17.26	18.82
Max	121.00	119.30	116.20	147.90	114.20	124.20	130.80
Min	34.50	33.40	34.00	34.70	31.60	38.40	40.20
Estimated Prices - Structural Model							
Mean	71.17	67.62	67.35	69.92	68.99	73.29	75.14
Standard Deviation	14.73	14.74	14.67	16.64	15.56	17.39	16.99
Max	108.45	104.37	104.16	117.02	108.55	117.57	128.56
Min	35.06	32.50	32.60	33.63	32.52	33.33	33.20

Table 3b: Descriptive Statistics by Formulation and Estimation Technique

	Formulation					
	Conventional	RFG	Ethanol-Blended RFG	CARB Gasoline	Jet Fuel	Distillate
Actual Prices						
Mean	70.24	72.54	75.85	81.81	65.72	64.35
Standard Deviation	17.25	17.75	19.69	20.81	16.96	17.13
Max	129.20	139.30	147.90	130.80	115.80	120.30
Min	34.40	38.50	43.00	49.40	31.60	31.70
Estimated Prices - Structural Model						
Mean	69.88	73.28	76.83	87.49	66.98	65.12
Standard Deviation	15.94	15.30	17.19	16.50	15.42	15.61
Max	117.57	118.64	117.02	128.56	111.61	109.41
Min	34.48	39.04	45.37	49.59	32.93	32.50

Table 4a: Counterfactual Results - Mean Wholesale Price by PADD

Simulation Run	PADD Region						
	1a	1b	1c	2	3	4	5
Predicted Prices - Base Case	71.17	67.62	67.35	69.92	68.99	73.29	75.14
Counterfactuals							
CARB Compatibility	71.45	67.92	67.49	70.03	69.12	73.36	74.87
Ethanol-Blended RFG Compatibility	71.16	67.93	67.15	69.72	68.53	73.75	75.21
Constant Refinery Ownership	70.22	66.52	66.35	68.68	68.06	72.04	73.98
2.5% Additional Refining Capacity	68.90	65.42	65.08	67.86	66.74	70.84	73.08
5.0% Additional Refining Capacity	66.93	63.49	63.07	66.02	64.72	68.76	71.29
7.5% Additional Refining Capacity	65.17	61.75	61.26	64.38	62.92	67.13	69.94

Table 4b: Counterfactual Results - Mean Wholesale Price by Formulation

Simulation Run	Formulation					
	Conventional	RFG	Ethanol-Blended RFG	CARB Gasoline	Jet Fuel	Distillate
Predicted Prices - Base Case	69.88	73.28	76.83	87.49	66.98	65.12
Counterfactuals						
CARB Compatibility	69.99	73.75	76.78	82.13	67.11	65.25
Ethanol-Blended RFG Compatibility	69.94	73.15	72.88	87.52	67.34	65.27
Constant Refinery Ownership	68.75	72.26	75.36	86.76	65.87	64.01
2.5% Additional Refining Capacity	67.73	71.08	74.88	85.21	64.65	62.80
5.0% Additional Refining Capacity	65.83	69.15	73.06	83.22	62.62	60.77
7.5% Additional Refining Capacity	64.18	67.42	71.61	81.51	60.89	59.05

Table 5: Simulated Wholesale Price Differential Due to Unexpected Refinery Outages
(cents per gallon, standard errors in parentheses)

State	Conditional on Outage Type			Unconditional
	Local Outage	Regional Outage	No Refinery Outage	
California	6.68 (1.33)		0.07 (0.02)	0.85 (0.16)
Illinois	7.28 (0.77)	2.38 (0.40)	-0.02 (0.01)	0.88 (0.29)
Wisconsin	7.72 (0.82)	3.47 (0.63)	0.00 (0.07)	1.46 (0.67)

Table 6: Simulated Wholesale Price Differential Due to Fuel Compatibility
(cents per gallon, standard errors in parentheses)

State	Conditional on Outage Type			Unconditional
	Local Outage	Regional Outage	No Refinery Outage	
California	9.26 (0.41)		4.46 (0.28)	5.36 (0.29)
Illinois	9.57 (0.47)	4.71 (0.76)	2.97 (0.14)	3.76 (0.45)
Wisconsin	9.92 (0.71)	5.01 (0.79)	2.86 (0.46)	4.17 (0.45)

Table 7: Simulated Wholesale Price Differential Due to Refinery Consolidation
(cents per gallon, standard errors in parentheses)

State	Conditional on Outage Type			Unconditional
	Local Outage	Regional Outage	No Refinery Outage	
California	1.41 (1.02)		0.54 (1.08)	0.73 (1.18)
Illinois	6.02 (0.14)	1.30 (0.51)	0.39 (0.19)	1.40 (0.10)
Wisconsin	5.45 (0.13)	1.11 (0.62)	0.65 (0.67)	1.54 (0.07)

Table 8: Simulated Wholesale Price Differential Due from Five Percent Increase in Refining Capacity
(cents per gallon, standard errors in parentheses)

State	Conditional on Outage Type			Unconditional
	Local Outage	Regional Outage	No Refinery Outage	
California	3.90 (0.35)		4.47 (0.34)	4.27 (0.26)
Illinois	3.85 (1.13)	4.31 (0.60)	3.86 (0.79)	3.78 (0.85)
Wisconsin	3.91 (1.19)	4.39 (0.62)	3.85 (1.31)	3.75 (0.82)

Note: Local outages for California are defined as in-state outages. Local outages for Illinois and Wisconsin are defined as outages in either Illinois or Wisconsin. Regional outages for Illinois and Wisconsin are non-local outages occurring within PADD 2 (IL, WI).

Table 9a: Descriptive Statistics For Simulations Based on Profit and Expected Profit Maximization, by PADD

	PADD Region						
	1a	1b	1c	2	3	4	5
Simulated Prices Based on Refinery Profit Maximization							
Mean	71.17	67.62	67.35	69.92	68.99	73.29	75.14
Standard Deviation	14.73	14.74	14.67	16.64	15.56	17.39	16.99
Max	108.45	104.37	104.16	117.02	108.55	117.57	128.56
Min	35.06	32.50	32.60	33.63	32.52	33.33	33.20
Simulated Prices Based on Refinery Expected Profit Maximization							
Mean	71.44	67.50	66.77	70.01	68.56	73.85	74.82
Standard Deviation	14.61	14.73	14.62	16.46	15.57	17.08	16.96
Max	108.24	104.16	103.96	116.76	108.36	117.32	128.16
Min	35.03	32.47	32.57	33.60	32.48	33.96	33.20

Table 9b: Descriptive Statistics For Simulations Based on Profit and Expected Profit Maximization, by Formulation

	Formulation					
	Conventional	RFG	Ethanol-Blended RFG	CARB Gasoline	Jet Fuel	Distillate
Simulated Prices Based on Refinery Profit Maximization						
Mean	69.88	73.28	76.83	87.49	66.98	65.12
Standard Deviation	15.94	15.30	17.19	16.50	15.42	15.61
Max	117.57	118.64	117.02	128.56	111.61	109.41
Min	34.48	39.04	45.37	49.59	32.93	32.50
Simulated Prices Based on Refinery Expected Profit Maximization						
Mean	69.77	73.35	76.38	87.15	67.03	65.12
Standard Deviation	15.89	15.19	17.10	16.41	15.28	15.44
Max	117.32	118.52	116.76	128.16	111.45	107.81
Min	34.74	39.12	45.91	49.59	32.92	32.47