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

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Abstract

Since 1999, gasoline prices in California, Illinois and Wisconsin have spiked occasionally well above gasoline prices in nearby states. In May and June 2000, for example, gasoline prices in Chicago rose twenty eight cents per gallon to \$2.13, while prices nationally rose only nine to \$1.73. Several qualitative studies identify unique gasoline formulations in California, Illinois and Wisconsin as crucial factors related to regional price spikes. This paper provides the first quantitative estimates of two distinct effects of state-level gasoline content regulations in California, Illinois and Wisconsin: (i) the effect of increased production costs associated with additional refining necessary to meet content criteria, and (ii) the effect of incompatibility between these blends and gasoline meeting federal reformulated gasoline (RFG) standards. Using a structural model based on the production optimization problem of refiners, I simulate wholesale prices for jet fuel, diesel and four blends of gasoline in each geographic market. I then specify a counterfactual in which gasoline in the three states only met federal RFG requirements. Using a constructed dataset of refinery outages, I am able to separately identify each effect. Using a similar methodology, I also estimate the effect of two other factors thought to increase gasoline prices, (i) changes in refinery ownership and (ii) limited expansion of domestic refining capacity.

Point estimates for the effect of increased refining costs are 4.5, 3.0 and 2.9 cents per gallon in California, Illinois and Wisconsin. The effect of incompatibility with federal RFG criteria, conditional on an in-state refinery outage, is 4.8, 6.6 and 7.1 cents per gallon in California, Illinois and Wisconsin. Controlling for the magnitude of local outages in these areas, I estimate that 72, 92 and 91 percent of price spikes created by local refinery outages could be mitigated by compatibility with federal RFG standards. I find that changes in refinery ownership in the late 1990's increase prices by 1.4 to 1.5 cpg in Illinois and Wisconsin and by 0.73 cents per gallon in California. 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.

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1 Introduction

Much of the recent interest in gasoline prices has focused on regional gasoline price spikes, that is price spikes geographically limited in scope from the city-level to the size of several states. An example of one such price spike occured in Chicago and Milwaukee in May and June, 2000. From May 30 to June 20, average prices of reformulated gasoline in Chicago and Milwaukee rose from $1.85 and $1.74 a gallon to as high as $2.13 and $2.02 a gallon. By July 24, gasoline prices dropped to $1.57 and $1.48 respectively.[1] In contrast, the national average price for reformulated gasoline during the same period varied less, rising from $1.64 on May 29, 2000 to $1.73 on June 19, 2000 and finally dropping back to $1.66 on July 24, 2000.[2] Similar price spikes are seen easily in Figures 1 and 2. Figure 1 shows the monthly average wholesale price for gasoline sold in the Chicago MSA and in California, along with the most closely tracked domestic spot price for crude oil, West Texas Intermediate (WTI) delivered to Cushing, OK. Figure 2 displays the differential between the two gasoline price series and the WTI crude spot price.

In Figure 2, price spikes in California and Illinois are apparent. Prior to 1999, wholesale gasoline prices in California and Illinois were, with a few exceptions, ten to thirty cents per gallon more expensive that the WTI crude spot price. Beginning in early 1999, though, wholesale prices in California and Illinois began to increase periodically above this established range. From January 1999 to December 2003, wholesale gasoline prices in Illinois spiked to more than forty cents per gallon above the WTI crude spot price on four occasions, with the largest spike, in Spring 2000, when gasoline prices spiked to over 70 cents per gallon above the WTI crude spot price. Over a similar period, California wholesale gasoline prices spiked over forty cents per gallon above the WTI spot price on nine occasions. In response to regional price spikes, several academic papers along with research by the FTC, EPA, Senate Subcommittee on Investigations and state commissions qualitatively analyzed structural changes in regional gasoline markets contributing to these spikes.[3] These studies identify three structural changes in the gasoline markets that potentially increase the frequency of regional price spikes: (1) inconsistent gasoline content regulations across different geographic regions, (2) declining reserve refining capacity, and (3) industry consolidation within the oil industry. In addition, these studies often identify incident-specific factors, including refinery outages, transportation constraints, reductions in product inventories, or transition costs associated with meeting new environmental regulations.

All studies identify the first factor, regional content regulations, as an important industry change related to regional price spikes. Over the past ten years, state and local regulations dictating the content of gasoline have reduced the fungibility of the domestic gasoline supply. In 1992, domestic gasoline met a single set of content standards. Ten years later, over fifteen different, and in some cases, mutually exclusive, blends of gasoline are mandated in different geographic areas. A simple model of quantity competition suggests gasoline content regulation likely has three distinct effects on gasoline prices.[4] First, blends of gasoline meeting content regulations are more

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[1] Final Report of the Federal Trade Commission on the Midwest Price Spikes, March 21, 2001

[2] EIA Motor Gasoline Watch; May 29, 2000; June 19, 2000; July 24, 2000.

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

[4] See Muehlegger (2002) for a discussion of gasoline content regulations and potential effects on refiners,

costly to refine than conventional gasoline. Second, additional refining costs associated with state-specific content regulations might influence which geographic regions refiners choose to serve. Finally, incompatible blends of gasoline may reduce the ability of refiners and marketers to move gasoline between geographic regions in response to supply and demand shocks. The first two are persistent effects and would increase average gasoline prices, but would have little effect on price volatility. The third only affects prices in the event of an unexpected supply or demand shock. The effect of the third, though, depends crucially on the degree of geographic differentiation across regions sharing compatible fuel standards. 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 refiners in other RFG-producing areas from sending gasoline to Chicago in response to a refinery outage. In this case, the transportation costs between geographic markets rather than the product heterogeneity would contribute most significantly to price spikes resulting from a local shock.

While previous government and academic studies identify factors which contribute to regional price spikes, no study quantifies the effect. This paper answers this question by providing a structural method which allows me to distinguish the effect of product heterogeneity from incompatible content regulations from the effect of geographic differentiation created by transportation costs. In particular, I focus on the effects on price levels and price spikes of the two most stringent regional blends of gasoline, ethanol-blended RFG sold in Chicago and Milwaukee and California Air Resources Board (CARB) gasoline sold throughout California. In addition to analyzing the effect of these regional gasoline content regulations, I simulate counterfactuals controlling for refinery consolidation and declining reserve refining capacity. These simulations estimate the effect changes in refinery ownership and the slow growth of refining capacity have on wholesale gasoline prices.

To quantify each of these effects, I specify a structural model of the refining industry based on the production optimization problem faced by individual refineries, including unobserved cost, conduct and elasticity parameters. Although the likelihood function for the structural model cannot be expressed in closed form, I numerically search for values of the unobservable parameters in the model that minimize the squared error between the solution to the optimization problem and the actual market-level production. Using values for parameters from the NLLS search algorithm, I then simulate prices of wholesale gasoline in Illinois, Wisconsin and California as if the states sold federal RFG instead of ethanol-blended RFG and CARB gasoline. This approach controls for transportation costs, refinery capacity constraints, changes in refinery ownership and gasoline compatibility. In order to distinguish the effects of content regulations on price levels and price volatility, I build a dataset of unexpected refinery outages. The set of refinery outages allows me to identify months with and without unexpected local supply shocks and hence months in which local gasoline content regulations affect prices in Illinois, Wisconsin and California through only increased production costs. Comparing simulated prices in months with and without local refinery outages separately identifies the effects of additional production costs of CARB gasoline and ethanol-blended RFG from the effects of incompatibility with

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transporters and marketers of gasoline.

federal RFG.

Section 2 discusses the relevant economic literature. Section 3 provides a background 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 reduced-form estimates of the effect of content regulations on price levels. In section 6, I propose a model of gasoline refining which allows me to estimate the effect of content regulations on regional price spikes and then estimate unobservable parameters of the model in section 7. In Section 8, I specify my primary counterfactual 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 9 concludes.

2 Previous Literature

This paper addresses two aspects of regional gasoline prices: (i) regional price volatility, changes in prices over time and (ii) price dispersion, differences in prices across state or regional markets. Several strands of literature relate to the topic and approach in this paper.

A considerable number of papers study gasoline price adjustment in response to shocks. These studies identify two empirical regularities observed in gasoline markets: prices are sticky, and prices adjust asymmetrically upwards and downwards. Explanations for the former include supply adjustment costs (Borenstein and Shepard, 2000), or menu-cost adjustment (Davis and Hamilton NBER 2003). The literature on asymmetric price adjustment focuses on crude oil price shocks (Borenstein, Cameron and Gilbert, 1997, and Bacon, 1991), but also addresses differences in search costs associated with different petroleum products (Johnson, 2002).

A second strand of literature estimates reduced-form effects of 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). These studies exploit cross-state variation in regulation or within-state changes in regulation over time, to estimate the effect of regulations on price levels.

This paper departs from a strictly reduced-form approach used in previous studies in favor of a structural approach like that used in Considine (2001) and Considine and Heo (2002), specifying a structural model based on the production optimization problem faced by individual domestic refineries. These studies incorporate a multiproduct optimal production problem of refiners into a structural model, considering refinery production of not only gasoline, but also jet fuel, distillate and other products. Unlike Considine and Considine and Heo, which aggregate individual refiner behavior into national prices and inventories, this paper optimizes the production decisions for individual refineries on a state-formula level. The production choice of individual refineries are modelled in light of refinery supply adjustment costs identified in Borenstein and Shepard (2000) and Muehlegger (2002). This approach allows me to control for factors that affecting regional price levels and volatility, but difficult to incorporate in a reduced-form approach, including refinery production constraints, changes in refinery ownership, transportation costs and gasoline product differentiation.

In addition to estimating the effect of regulations on price levels and spikes, this paper also identifies the extent to which product heterogeneity and geographic differentiation contribute to product differentiation of wholesale gasoline markets in California, Illinois and Wisconsin. 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 details, the structure I impose on my model allows for the simulation of several counterfactuals.

3 Industry Overview

3.1 Wholesale Gasoline Sales

3.1.1 Vertical Industry Structure

The domestic petroleum products industry consists of several vertically-structured tiers: (i) Refining of crude oil, (ii) Transportation of refined products by pipeline or barge to regional terminals, (iii) Storage and wholesale sale at regional terminals, (iv) Transportation by truck to retail stations and (v) Retail sale. I first discuss the general technology and spatial organization of the industry and then discuss how the specific industry characteristics contribute to wholesale price volatility spikes.

Refineries perform the initial production step, separating crude oil into different intermediate product streams. Depending on the production units, some refineries alter the chemical properties of these streams (e.g. desulfurization). After any alterations, the refiner blends the streams into a variety of end-products.[5] End products are classified into light products, including gasoline, jet fuel, kerosene and diesel fuel, and heavier products, which include industrial products such as fuel oil and coke. The chemical properties of light products allow them to be sold to consumers at high prices relative to heavier products sold to industrial customers. Due to the relative price premium associated with light products, the refiners maximize production of light products subject to capacity constraints of refinery production units. Although refiners maximize light product production, refiners trade off production between light products in response to relative prices. In total, 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]

Domestic refineries are concentrated geographically in Texas, Louisiana and California, with over fifty percent of national distillation capacity located in the three states.[7] Remaining domestic refining capacity is sited near specific end markets (e.g.

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[5] End-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. Depending on the use of the end-product, the product must meet criteria along the various dimension. This, in turn, dictates which intermediate streams a refiner can combine to create the product.

[6] Although 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.

[7] Distillation is the first step in the refining process, where the refinery heats and separates crude oil based on boiling point. As of January 1, 2002, total domestic atmospheric distillation capacity was 17.6 million

New Jersey and Illinois) or other sources of crude oil (e.g. Wyoming). As a result of the geographic concentration of refining assets, the East Coast, upper Midwest and occasionally the West Coast import gasoline from the Gulf Coast to meet regional demand. To supply these markets, refiners ship petroleum products by barge or pipeline to regional wholesale terminals located throughout the United States.

Wholesale terminals serve as a point of sale for industrial and wholesale customers and as a short-term storage point. 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, wholesale terminals are located near most metropolitan areas.

I focus on two crucial aspects of refinery operation which contribute to price volatility and inform my structural model introduced in section 6. First, substantial supply adjustment costs exist due to both specifics of refinery operation and the spatial organization of the industry. Second, refiners must occasionally stop production unexpectedly due to fires, explosions or other accidents. Slow response by unaffected refiners to localized supply outages creates regional price volatility, which regional content criteria exacerbate.

3.1.2 Refinery Operation and Price Volatility

Two aspects of domestic refining affect the speed with which refiners respond to local shocks, (i) supply adjustment costs and (ii) transportation lags between geographic markets. Supply adjustment costs exist since it is costly for a refinery to deviate from a pre-planned production schedule. Supply adjustment costs arise since refiners must contract in advance for crude oil and optimize refinery operation based on the crude properties. Refiners contract for crude oil, several months prior to production, based on the properties of the crude, expected demand for end-products and existing refinery capital. The properties of the chosen crude oil and the processing units at a particular refinery in turn define the set of end-products a particular refinery can produce. Just prior to production, a refiner re-optimizes refinery production based on updated prices and the characteristics of the crude oil.

While refiners can adjust the mix of end-products they produce in the long run, by purchasing different crude oils and changing the operation of the refinery. Significant production adjustment costs exist in the short run, when the crude oil choice is fixed and changes to refinery operation would require slowing production. Once the production run begins, a refiner must either alter the operation of production units or blend intermediate streams in a different way to achieve a different mix of end-products. A refinery can often only increase the quantity of one high-value end-product, such as gasoline, by blending a greater proportion of high quality intermediate streams.[8]

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barrels per day - 25, 16 and 12 percent of this capacity was located in Texas, Louisiana and California respectively.

[8] Like refined end-products, the properties of intermediate streams from individual processing units differ significantly. For example, straight run gasoline, extracted directly from the distillation tower, has low octane value (70-75) and high Reid vapor pressure, while alkylate has higher octane (90-95) and lower Reid vapor pressure. In order to produce gasoline meeting RVP limits and minimum octane content, these two streams, along with others, must be blended together.

This leaves the refinery with more lower value petroleum streams it either must blend into an end-product, reducing its quality, or sell at a low price on the market. Thus, a refinery incurs significant costs when altering the production mix after a production run begins. In addition, adjustment costs are greatest for end-products meeting the highest specifications, such as gasoline. These products require a refiner to make large changes in blending to continue to meet content requirements for different fuels. As a result of supply adjustment costs, refiners plan production runs several months in advance, beginning when they contract for the crude oil and plan initial refinery operation. During the production runs, which generally last three to six weeks, the refiner makes only small changes to the mix of end-products and to the operation of particular units. Since refiners often finish production runs prior to adjusting production mix, supply adjustment costs slow refinery response to supply or demand shocks.[9]

Transportation lags also slow industry response to localized shocks. As mentioned above, domestic refineries are relatively concentrated. Geographic concentration of refineries implies that areas with excess demand (e.g. Midwest and East Coast) must import petroleum products from areas with excess supply (e.g. Gulf Coast).[10] Even if refineries could adjust production immediately in response to shocks, the time to transport gasoline by barge or pipeline also slows the response of the market to a shock. It takes ten to fourteen days to pipe gasoline from the Gulf Coast to Chicago and fourteen to twenty-two days to pipe gasoline from the Gulf Coast to Newark. A similar three week lag exists to barge gasoline from the Gulf Coast to California.

The presence of supply adjustment costs and transportation delays do not necessarily imply a market with regional price spikes. In addition to these two factors, a source of unexpected regional supply or demand shocks must exist and regional inventories must be insufficient to mitigate the supply or demand shocks. I focus on exogenous refinery outages, caused by fires, explosions or lightning, as significant regional supply shocks. Although wholesale terminals do carry inventories, inventories held constitute only two to three weeks of consumption. In addition, although inventories exist, operational constraints of storage limit the degree to which storage can mitigate a supply shock caused by a large refinery outage.

3.2 Content Regulations and Boutique Fuels

An additional industry feature, which increases the effect of refinery outages on domestic gasoline prices, is that gasoline is a differentiated product, due to state-level gasoline composition regulation.[11] In 1992, the Amendments to the Clean Air Act initially mandated federal content criteria for gasoline in regions failing to meet EPA limits for ozone and carbon monoxide pollution. Recognizing that mobile-source air pollution depends not only on emissions, but also on the climate, the 1992 Amendments 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. For each of these blends of gasoline, the

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[9] See Muehlegger(2002) and Borenstein and Shepard (2001) for a discussion of supply adjustment costs in crude oil refining.

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

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

federal regulations specify standards for two general gasoline characteristics: oxygen content and volatility. Increasing the amount of oxygen in gasoline improves the combustion of gasoline when the weather is cold and reduces carbon monoxide emissions. Decreasing volatility reduces the propensity of gasoline to evaporate and reduces ozone emissions.[12] The EPA mandate only specifies minimum standards, though allowing states to supplement the federally-mandated content requirements, either by voluntarily imposing federal requirements or by mandating more strict regulations than the federal standards.[13] As a result of supplementary standards, in 2001, fifteen distinct blends of gasoline were used in the lower 48 states.

California, Illinois and Wisconsin impose the most strict standards relative to those mandated federally.[14] Standards for California 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 must meet identical volatility and oxygen content standard to federal RFG, but must 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 gasoline to blend with ethanol to meet the volatility requirement of federal RFG. As a result, gasoline meeting federal RFG requirements cannot be 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.

In this paper, I focus specifically on the effects of CARB and ethanol-blended RFG since, unlike other regulations, these require refinery-level production adjustments to meet content specification. These are in contrast to oxygenated gasoline, which only requires refiners to supplement the oxygen content of conventional gasoline. Increasing production of either CARB gasoline or Ethanol-blended RFG requires a refinery to alter the blending of intermediate streams and potentially entails supplementary processing (eg. the removal of sulfur for CARB gasoline). Thus, these fuels are the ones most likely to entail substantial supply adjustment costs, and the ones most likely to be affected by unexpected supply shocks.

3.2.1 Other Changes Contemporaneous with Content Regulations

Complicating an analysis of price spikes are structural changes in the industry concurrent with changing content regulations. Substantial industry consolidation has occurred over the past decade. [15] Although required asset divestiture limited increases in refinery concentration, changes in ownership still may affect competition between refineries. In addition to industry consolidation, there has also been a trend toward

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[12] Ground-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.

[13] Opt-in to the federal RFG program accounts for approximately one-third of RFG consumption.

[14] Although the focus of this paper, Illinois, Wisconsin and California are not alone in mandating special blends of gasoline. Currently, 15 different blends of gasoline exist across the country. For an in-depth discussion of boutique fuels and the potential effects, see Muehlegger(2002).

[15] Large 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.

decreasing reserve refining capacity over the past twenty years. In 1981, annual refinery production was 68 percent of refinery capacity.[16] Due to closure of old refineries, increasing demand and only incremental changes to refining capacity at existing sites over the past twenty years, current utilization of refining capacity exceeds 95 percent. As a result, unexpected refinery outages could increase local wholesale prices simply by virtue of little spare production capacity existing in the current industry.

3.3 Regional Price Volatility and Refinery Outages

This paper examines the extent to which content regulations in Illinois, Wisconsin and California contribute to gasoline price volatility resulting from unexpected refinery outages.[17] Fires and explosions at refineries are unpredictable, localized, and, in many cases, necessitate maintenance of a significant portion of the local refining capacity. An example of such an event is the fire that damaged the Lemont, IL distillation unit on August 14, 2001, closing the refinery for six weeks and reducing production for several months thereafter. While not the largest refinery in Illinois, Lemont accounts for 16 percent of Illinois' distillation capacity.

The geographic nature of refining and transportation, local content regulation and supply adjustment costs have the potential to contribute to regional price volatility. In the event of an outage of a plant producing either ethanol-blended reformulated gasoline or California Air Resources Board gasoline, such as the Lemont refinery, incompatible standards prevent nearby refiners producing other gasoline blends from selling them in these areas. In addition to transportation lags and supply adjustment costs, which slow the speed at which refineries respond to shocks, incompatible content regulations might additionally constrain refinery response to supply shocks. Thus, these regulations have the potential to compound the effects of an unexpected refinery outage, especially in the case of gasoline formulations with no substitutes such as ethanol-blended RFG or CARB gasoline.

4 Data

I collect two sets of data with which I estimate reduced-form and structural models: (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 average rack price and total wholesale 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 observations, beginning Jan 1995 and ending with Dec 2001, after the Midwest and California price spikes of 2000 and 2001. For gasoline, the EIA data tracks prices and volumes monthly by state and federal formulation standard (RFG, oxygenated,

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

[17] Pipeline outages, which are not explicitly modelled in this paper, can act in a similar manner to supply shocks. As an example, a pipeline outage contributed to high gasoline prices in Phoenix, AZ in September 2003.

and conventional gasoline).[18] For prices in both the reduced-form regressions and the structural model, I use average monthly rack price net of taxes for each state-formulation combination for gasoline. 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. The EIA data do not differentiate between branded rack sales (eg. sales of Chevron gasoline) and unbranded rack sales. 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.[19] Volumes for all products are prime supplier volumes, sales by wholesale marketers to retailers. This classification represents the closest analogy to wholesale volumes. To verify that prime supplier volumes are representative of wholesale gasoline volumes, I compare the EIA prime supplier gasoline volumes to state-reported monthly wholesale gasoline sales reported to the Federal Highway Administration.[20]

The EIA Petroleum Marketing Monthly only tracks gasoline sales by federal-formulation standard, and does not specifically track regional blends exceeding federal requirements. Although sales of CARB gasoline or ethanol-blended reformulated gasoline are not identified in the EIA data, both gasoline blends meet federal-RFG standards and are reported as such in the dataset. In addition, no other gasoline blends in California, Illinois and Wisconsin meet federal RFG standards. Thus, I attribute all reported RFG sales in these states as either a sale of CARB gasoline or ethanol-blended RFG depending on the state. For the structural model, I aggregate conventional and oxygenated gasoline, since oxygenated gasoline is only differentiated from conventional gasoline by the addition of oxygenate at the refinery or terminal and does not require incremental refinery-level processing. Therefore, 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. As a result, my panel of market-level data consists of 84 monthly observations for each of 62 markets for gasoline, defined by state and federal formulation standards, eight regional markets for jet fuel and eight regional markets for diesel fuel.[21]

To simulate refinery behavior, 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. For the simulation, I

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[18] Ideally, 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, in the event on a local refinery outage and spike within a particular area.

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

[20] Although 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.

[21] Sixty 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. For purposes of this paper, each of these is treated as a separate market for gasoline.

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.[22] Of the 173 domestic refineries operating at some point during the study period, I consider the subset of 117 refineries 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.[23]

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.[24] 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.[25] 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,

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[22] Specifically, 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.

[23] Many 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.

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

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

in the structural model, I take imports to be exogenous.[26] 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 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. From Jan 1995 to Dec 2001 for the 117 domestic refineries in the sub-sample, I identify a total of 121 incidents, forty-five of which necessitated the shutdown of one or more processing units. 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 Reduced-Form Regression

5.1 Data and Estimation

I initially use a reduced-form model to estimate the effect of gasoline content regulations on price levels. The general specification for the panel regression I use is given by

$$P_{ijt} = f(Q_{ijt}, W_{ijt}, Reg_{ijt})$$
$$Q_{ijt} = g(P_{ijt}, Z_{ijt})$$

where i denotes state, j denotes blend, t denotes time, P_{ijt} is the real rack price of gasoline, Q_{ijt} is the volume of gasoline sold for resale, W_{ijt} is a vector of production input costs, Reg_{ijt} is a vector of content regulation variables and Z_{ijt} is a vector of income and other demographic variables. To consistently estimate the coefficients of the first equation, I use the vector of demand factors exogenous to price, Z_{ijt}, to instrument for quantity in the first equation. Table 2 lists descriptive statistics for the variables used in the reduced-form model. This approach implicitly treats content regulation as exogenous to price. Regulation is exogenous to price for areas required to adopt either RFG or oxygenated gasoline due to non-compliance with Clean Air Act standards. For areas opting into the federal programs, if a state decision is endogenous to gasoline price, states for which content regulations are more costly would be less likely to opt-in. Thus, treating regulation as purely exogenous provides a conservative estimate of the mean price effect.

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

In order to estimate coefficients for content regulation, consider the fixed-effects panel regression corrected for AR(1) errors

$$P_{ijt} = \alpha + \beta_0 Q^Z_{ijt} + \beta_1 WTI_t + \gamma Reg_{ijt} + \nu_i + \phi_{ijt}$$

$$\phi_{ijt} = \epsilon_{ijt} + \rho\epsilon_{ijt-1}$$

$$\epsilon_{ijt} \sim N(0, \sigma^2_{ij})$$

where ν_i denote state fixed-effects, Q^Z_{ijt} instrumented quantity, WTI_{ijt} West Texas Intermediate crude oil spot price delivered to Cushing, OK, instrumented by the Brent North Sea crude spot price, and Reg_{ijt} content regulation dummy variables identifying blends meeting oxygenated gasoline, RFG, ethanol-blended RFG and CARB gasoline requirements.[27] In subsequent specifications, I also include month-year fixed effects and month-region fixed effects. In each of these specifications, states entering and leaving the programs and states with more than one specification of gasoline identify of the effect of regional content regulations. Table 3 presents the coefficients and standard errors for three model specifications. Errors are assumed to follow an AR(1) process within state-blend panels with a common autocorrelation coefficient ρ, and are heteroscedastic across state-blend pairs.

I also run fixed-effects regressions for several alternative specifications. Specification 2 uses WTI crude spot price with a vector of month-year fixed effects, and specification 3 allows for month fixed effects which vary by PADD. The second specification allows for a more flexible common time-trend than the specification including WTI crude spot price. The third specification allows for different monthly trends for each region. In each regression, ethanol-blended RFG and CARB gasoline dummy variables are additive with respect to the RFG dummy. Thus, the coefficients for either the ethanol-blended RFG or CARB dummies represent the effect on price levels from more strict regulation, relative to federal reformulated gasoline.

Looking at the first specification, the coefficients on content regulation dummies are positive and sign-consistent with ex-ante predictions of increased production costs of CARB gasoline, RFG and oxygenated gasoline relative to conventional gasoline. The coefficients of the content regulations dummies are statistically significant at the one percent level. Relative to conventional gasoline over 1995 to 2001, oxygenated gasoline and reformulated gasoline rack prices are 3.5 and 3.8 cents per gallon higher than conventional gasoline. In addition, ethanol-blended RFG and CARB gasoline rack prices are 1.8 and 3.2 cents per gallon higher than federal RFG, although each point estimate is imprecisely estimated.[28] Allowing for state-specific monthly trends in specification 3, the estimated price effect of the regulations are 4.9 cpg and 4.2 cpg for oxygenated gasoline and federal RFG relative to conventional gasoline, and 1.7 cpg and 5.1 cpg for ethanol-blended RFG and CARB gasoline relative to federal RFG. These estimates are consistent both with EPA estimates of the incremental cost of federal RFG over conventional gasoline of four to eight cents per gallon, historical

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[27] A Hausman specification test of the random effects model indicates that $E[\epsilon, \nu] \neq 0$, necessitating the use of a fixed-effects specification.

[28] It is important to note that oxygenated and reformulated gasoline also have lower energy content than conventional gasoline due to the addition of oxygenates. These blends reduce mileage per gallon in cars by 2-3 and 1-2 percent respectively. This effect is not incorporated into these regression, but would increase the price level effect of these regulations.

Chicago/Dallas RFG price differentials of six to eleven cents per gallon, and California Air Resource Board estimates of incremental costs of CARB gasoline standards of five to fifteen cents per gallon.[29]

5.2 Structural Model Justification

The reduced-form model provides a consistent estimate of the effect on wholesale price levels of federal and regional gasoline content regulations. In order to identify the effect of content regulations on regional price spikes, though, I formulate a structural model of refinery production decisions. The structural model allows me to simulate counterfactuals in which California, Illinois and Wisconsin alternatively mandate gasoline blends that meet only federal RFG requirements. A proper counterfactual is difficult to formulate in the reduced-form model. For example, a counterfactual in which California gasoline meeting only federal-RFG standards must control for transportation costs from other sources of federal-RFG. If transportation costs are sufficiently high, compatibility with federal-RFG standard may not mitigate the effect of an unexpected refinery outage. A structural model allows me to control for this, by simulating the production decisions of refiners which incorporate transportation costs and changes in refinery ownership.

6 Structural Model of Supply Shocks

To simulate an accurate counterfactual, I specify a structural model based on the production optimization problem of refineries, which allows me to identify the effect of incompatible regulations coming from production costs, changes in competition due to incremental production costs and changes in the response of refineries to unexpected outages.

I consider a three step game in which refiners choose quantities of light petroleum products to maximize an objective function subject to changing information about refinery outages. Consistent with refinery planning prior to production runs, refineries make production decisions in the first step without knowing outages. Outages are then realized and observed by refineries. Finally, since refineries can reallocate production, but supply adjustment costs exist, refineries re-optimize production in the final step in response to the outage, under the constraint that the product mix chosen in the first step is unchanged. Thus, a refinery choosing to produce federal RFG, but not CARB gasoline, could choose to redistribute federal RFG from one market to another in response to an outage, but can not, in the short term, choose to produce CARB gasoline instead.

In the first step, I assume that refineries have knowledge of all supply and demand variables with the exception of the unexpected outages occurring in the current period. That is, prior to choosing initial production at time t, refineries know the inverse residual demand curve accounting for imports, $p_{jt}(.)$, in each geographic and product market $j \in \{1, 2, \ldots, J\}$ in addition to input costs for all refineries. For each domestic refinery, $i \in \{1, 2, \ldots, I\}$, let q_{ijt} be the initial choice of quantity in market j at time t, $\overline{q}_{it}$

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[29] See Testimony of R. Perciasepe and Testimony of C. Browner before US House of Representatives, Commerce Committee, July 2000 (http://www.epa.gov/ocir/hearings/testimony/) and Bulow et al. at page 146

denote the total production capacity of all light petroleum products, $c(q_{i1}, q_{i2}, \ldots, q_{iJ})$ be the refinery production cost function and t_{ij} denote the transportation costs from refinery i to market j.

In the second step, refinery outages and severity are realized and fully observed by all refineries.

In the third step, refiners re-optimize their production decisions in response to the realization of outages $\omega \in \Omega$. Refineries are allowed redistribute their production from step 1 across geographic markets, but not across blends . Thus, I denote $\{J_1, J_2, \ldots, J_n\}$ a proper partition of markets $\{1, 2, \ldots, J\}$, where all markets sharing a given set of content regulations belong to one element of $\{J_1, J_2, \ldots, J_n\}$.[30] Given a partition of the markets based on product characteristics, in the third step, a refiner owning a set of refineries $\tilde{I} \subset \{1, 2, \ldots, I\}$ chooses a vector of Nash quantities $\{\tilde{q}_{ijt}\}$ for $i \in \tilde{I}$ to maximize an objective function consisting of own-refinery profits plus a portion of non-own refinery profits, captured by the coefficient of competition, α.[31] That is, the objective function of a particular refiner is given by

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

where Π_{it} is given by

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

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

$$\begin{aligned}
\tilde{q}_{ij} &\geq 0 \text{ for all j} \in \text{J} \\
\sum_{j \in J_1} \tilde{q}_{ij} &= \sum_{j \in J_1} q_{ij} \\
\sum_{j \in J_2} \tilde{q}_{ij} &= \sum_{j \in J_2} q_{ij} \\
&\cdots \\
\sum_{j \in J_n} \tilde{q}_{ij} &= \sum_{j \in J_n} q_{ij}
\end{aligned}$$

Note that in this specification, a value of $\alpha = 1$ implies joint profit maximization by all refineries and $\alpha = 0$ implies a single-period game in quantities. For refineries affected by an outage at time t and with initial production exceeding post-outage refinery capacity, production is scaled back evenly across all products.

Prior to the realization of outages, the refinery chooses a binding production mix, which it is then able to allocate in response to outages. Once the refinery commits to a production mix in the first step of the optimization, it is constrained to that mix after the realization of outages, consistent with substantial industry supply adjustment costs

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

[31] See 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.

within, but not between, production runs. Thus, in the first step, refiners choose preplanned production 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 non-own refinery profits, α. The objective function for a refiner owning refineries $\tilde{I} \subset \{1, 2, \ldots, I\}$ is given by

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

subject to refinery capacity and non-negativity constraints

$$\begin{aligned} q_{i1} + q_{i2} + \ldots + q_{iJ} &\leq \overline{q}_i \\ q_{ij} &\geq 0 \end{aligned}$$

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

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

In the first step, the expectation is taken with respect to the continuous state space of all possible refinery outages. In order to numerically solve for the equilibrium, 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 to this assumption 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.[32] When choosing production, refiners weigh the benefits of additional 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 simulated, the magnitude of the effect is over an order of magnitude less than the effect of the content regulations.

Given the specification of the game above and suppressing the time subscript, initial choice of production for market j by refinery i satisfies the first order condition

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

where λ_i denotes the shadow cost of production capacity at refinery i and μ_{ij} denotes the non-negativity constraint. In the event of an refinery outage, the final choice of

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[32] Recall that over the seven year period, news, industry and government sources document only forty-five production-lowering outages. Over the seven year period, the expected monthly percentage of total refinery capacity down due to an unexpected outage is 0.2 percent.

production satisfies

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

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

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

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

To complete the model, I make functional form assumptions for the cost and demand functions, $c(q_{i1}, q_{i2}, \ldots, q_{iJ})$ and $p_{jt}(.)$. Let the refinery production cost function be additively separable and let the marginal cost of refinery i to produce a fuel for market j at time t be

$$\begin{aligned} MC_{ijt} &= \beta_0 + \beta_1 * OilPrice_{it} + \beta_2 * Log(DC_{it}) + \\ &\quad \beta_3 * RFG_j + \beta_4 * ERFG_j + \beta_5 * CARB_j + \beta_6 * JF_j + \beta_7 * DIST_j \end{aligned}$$

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 RFG_j, $ERFG_j$,$CARB_j$, JF_j and $DIST_j$ are dummy variables corresponding to reformulated gasoline, ethanol-blended RFG, CARB gasoline, jet fuel and distillate.[33] This choice of functional form for the cost function captures both the differential production costs for various products, as well as economies of scale in refinery production, as the coefficient on the log of distillation capacity. Moreover, it allows for region-specific crude prices, incorporating both the price of local crude streams and transportation to the refinery.

I take $p_{jt}(.)$, the inverse demand function for market j at time t, to be linear given by the functional form

$$p_{jt}(q_{jt}) = p_{jt}^A + (\frac{-p_{jt}^A}{\epsilon q_{jt}^A})(q_{jt} - q_{jt}^A).$$

where p_{jt}^A and q_{jt}^A are the observed price and quantity in market j at time t. This specification is equivalent to a first-order taylor approximation of a isoelastic demand curve, $q_{jt}(p_{jt}) = \frac{\gamma}{\epsilon}p_{jt}^{\epsilon}$, taken at the observed price and quantity in market j at time t.

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[33] Although 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.

7 Structural Estimation

7.1 Assumptions and Estimation

Absent the functional form specifications for the cost and demand functions, the three-step model in the previous section defines a deterministic correspondence, which I denote $f : (X, \theta) \rightarrow Y$, between factors influencing refinery supply decisions, such as content regulations, input and transportation costs collectively denoted (X), and the vector of unobserved parameters (θ), which includes unobserved cost, conduct and elasticity parameters, and market-level prices and quantities (Y).[34] That is, f maps a given state space and values for unobservable parameters to all market equilibria that are solutions to the refinery optimization problem. Given the functional form specifications, the set of FOCs for the model simplifies to a full-rank linear problem. Thus, the functional form assumptions provide a sufficient condition for f to be a function, implying a unique solution to the optimization problem. Since the model contains unobservable parameters for refinery conduct and production cost, prior to simulating the effect of the content regulations, I first estimate the vector of unobservable cost, conduct and elasticity parameters, θ.

In order to estimate the unobserved parameters, I introduce a stochastic error term into the demand curve of each market, that is common to all refiners, and realized after refiners choose quantities in each market. I take $\delta_{jt} \sim N(0, \sigma^2)$ to be an additive stochastic shock to the inverse demand curve for market j from the previous section,

$$p_{jt}(q) = p_{jt}^A + \delta_{jt} + (\frac{-p_{jt}^A}{\epsilon q_{jt}^A})(q_{jt} - q_{jt}^A).$$

I assume that δ_{jt} is independent and identically 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. For example, unexpectedly good or poor weather might constitute a shock to demand, common yet unpredictable to all refiners serving a particular market. Linearity of the refiner FOC's implies a structural functional form given by the non-linear regression

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

Due to the three-step nature of the model, the associated likelihood function cannot be expressed as a closed function of the vector of unobserved parameters.

Thus, I numerically search for the NLLS set of parameters, that is, $\hat{\theta} = argmin_{\theta}((f(X, \theta) - Y)'(f(X, \theta) - Y))$. 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.[35] As part of my robustness checks, I test the sensitivity of my simulation results to variations in the NLLS parameter point estimates.

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[34] The set of unobservables, denoted θ, consists of the eight cost parameters $\{\beta_1, \beta_2, \ldots, \beta_8\}$, the conduct parameter α and demand elasticity parameter ϵ.

[35] In 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, $\alpha = .15, \beta_0 = 5, \beta_1 = 1, \beta_2 = -1, \beta_3 = 5, \beta_4 = 8, \beta_5 = 10, \beta_6 = -2, \beta_7 = -4$, is based on an initial simulation of PADD 5 only and ex-ante government estimates for production costs of different gasoline blends.

7.2 Estimated Parameters and Interpretation

Table 4 lists the NLLS estimates for $\hat{\theta}$. The point estimates are consistent with expectations. The coefficient on crude cost, β_2 is smaller but still relatively close to the ex ante prediction of 1. The coefficient on log distillation capacity, β_1, is less than 0 and consistent with increasing returns to distillation capacity. Cost parameters corresponding to differential production costs for different product blends are similar to government and industry estimates. The incremental production costs 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. Although it is possible to reject the null hypothesis that the coefficient of competition is 0, the estimated value of α is 0.03, consistent with almost complete own-profit maximization by refiners. Repeated interaction could enable tacit collusion amongst refiners - in such a world, tacit collusion would reduce production below the levels which maximize own-refiner profit in the static game. In other words, refiners place positive weight on the profits of other refiners, that is a positive value of α. The small point estimate for α suggests tacit collusion is not prevalent, consistent with the conclusions of academic and non-academic studies.[36]

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. My estimate of the short run elasticity, -0.337, is slightly more elastic than the median and mean of the sample collected in Espey, but is well within the range of sample estimates of 0 to -1.36.[37] In addition to other robustness checks, I verify my conclusions are unchanged by using a demand elasticity of -0.23.

7.3 Model Fit

As important as reasonable estimates of the parameters is the degree to which the structural model accurately simulates prices across the different product and geographic markets. It is also important that the model predict price spikes resulting from unexpected refinery outages. I use two metrics to measure the fit of the simulated and 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 simulation accurately models factors which lead to differences in wholesale prices across products and geographic markets. Table 5a and 5b list descriptive statistics for actual and estimated prices across different petroleum products and different PADD regions. For comparison, I include the estimated price from both the structural model and the reduced-form model. The reduced-form and structural models draw from identical samples, with the exception that the reduced-form model does not estimate prices for jet fuel and diesel.

Both the mean and standard deviations for the simulated wholesale prices are similar across blends and regions to mean and standard deviations of actual prices. Across geographic regions, all estimates from the structural and reduced-form models are

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[36] See, in particular, Bulow et al. (2003) and FTC Midwest Price Spike Investigation (2001).

[37] As 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.

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 structural and reduced-form models are near actual estimates 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 and 27 cpg for the structural and reduced-form models, respectively. The underestimation is the result of the simulation not fully predicting the Spring 2000 price spike for ethanol-blended RFG. While several refinery outages occurred in Spring 2000, these do not sufficiently explain the large change in the price ethanol-blended RFG.[38] During this period, ethanol-blended RFG was first required to meet more strict federal Phase II guidelines. Initially, refiners had difficult meeting Phase II emission guidelines while continuing to use ethanol as an oxygenate. This transition contributed to high prices of ethanol-blended RFG in Spring 2000, and importantly, as an initial, but not persistent, difficulty with producing ethanol-blended RFG, is not accounted for by the simulation model. Hence, simulated prices are substantially below actual prices for ethanol-blended RFG during May 2000.

To assess the degree to which the model accurately captures the effect of outages, I first-difference the simulated and actual wholesale prices in months with unexpected local outages. Although the model does not predict the Spring 2000 price spike in the Midwest, the model does predict wholesale price responses to local outages well. The simulated mean 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 mean 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.

8 Simulation Results

Using the NLLS estimates of the cost, conduct and elasticity parameters, I simulate wholesale prices under several counterfactuals to estimate the degree to which content regulations, industry consolidation and declining reserve capacity affect price levels and price spikes. I also test the sensitivity of the simulation results to variations in the NLLS estimated parameters and modelling assumptions.

8.1 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

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

refinery outages. To quantify the effect of these regulations, I simulate counterfactual prices for each of my 78 markets treating CARB and then ethanol-blended RFG as if the content regulations simply met federal RFG standards. For the counterfactual, I keep all outages, changes in ownership, capacity additions, and input costs identical to those in the base case. Thus, the only difference between the base case and initial counterfactuals is the change in gasoline content regulation.

Treating gasoline standards in California, Illinois and Wisconsin as compatible with federal RFG standards has three market effects. First, production costs for federal RFG are lower than those for either CARB gasoline or ethanol-blended RFG. A second related effect is that increased production costs may cause refineries to make different production choices under non-outage conditions. Finally, in the event of a local refinery outages, regional standards prevent adjustment by refiners across geographic markets, which would occur but for incompatible content regulations. NLLS estimates for cost parameters identify the first effect, the incremental production costs associated with CARB or ethanol-blended RFG. I distinguish the second and third effects by identifying months in which unexpected local refinery outages occurred in California, Illinois and Wisconsin. For months without outages, the first two effects alter prices while for months with unexpected outages, all three have an effect on the market price.[39] Thus, the average price differential between the base case and counterfactual in months without local outages identify the persistent effects of additional production costs. The difference in the average price differential in months with local outages and months without outages identify the effect of incompatible content regulations. For outages exceeding a month in duration, I only consider the first month of the outage, since refiners subsequently adjust production mix after the first month to account for the outage.

I calculate the average differential between the simulated price in the base case, with existing content regulations in CA, IL and WI, and the simulated price in the counterfactual, where regulations in CA, IL and WI are compatible with federal-RFG. In particular, I calculate the average differential conditional on whether or not an unexpected local outage occurred, as well as unconditional on outage. I list the average price differentials in Table 8. The differential in months without outages (column 3 in Table 8) identifies the persistent effect of increased production costs. The average price differential in months with local outages (column 1) identifies the effects of both increased production costs and content regulations incompatible with federal RFG criteria.

The point estimates of price effects of additional production costs associated with content regulations in California, Chicago and Milwaukee are 4.5, 3.0 and 2.9 cents per gallon. That is, conditional on outage-free operation of all domestic refineries, average wholesale price in California, Chicago and Milwaukee would be 4.5, 3.0 and 2.9 cents lower if areas required federal RFG instead of CARB and ethanol-blended RFG respectively. Conditional on a local outage in California, Illinois and Wisconsin, content regulations inconsistent with federal RFG standards raise wholesale gasoline prices in California, Chicago and Milwaukee 9.3, 9.6 and 9.9 cents on average.[40] Since months

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[39] Note this makes an implicit assumption, supported both by the simulation results and actual data, that local refinery produce the vast majority of CARB gasoline or ethanol-blended RFG.

[40] Substantial variation exists across specific local outages - in months with the largest outages in California, Illinois and Wisconsin, simulated prices with local content regulations are 20 cents per gallon higher than

with local outages provide a point estimate of the combined effect of increased production costs and incompatible regulations, removing the portion of the price changes attributable to additional production costs provides an estimate of the portion of the price spikes attributable solely to incompatible fuel regulations. Taking the difference between the differential contingent on a local outage and the differential contingent on outage-free operation (ie. the difference between Column 1 and Column 3 in Table 8), I find that incompatible content regulations raise prices 4.8, 6.6 and 7.0 cents per gallon in California, Illinois and Wisconsin.

Since actual refinery outages vary in severity and duration, the greater effect of fuel incompatibility in Chicago and Milwaukee could be simply a result of the magnitude of local refinery outages experienced in Illinois and Wisconsin. That is, if refinery outages in Illinois and Wisconsin were of greater magnitude or of longer duration than outages in California, the effect of content regulations would appear greater due entirely to differences in local outages. As a way to control for the severity and duration of local shocks, I simulate market prices under another counterfactual, in which local content regulations exist but no refinery outages occur. Comparing simulated prices in this counterfactual to those in the base case provides an estimate of the magnitude of the outages in California, Illinois and Wisconsin. For example, to estimate the effect of local refinery outages on California, I simulate gasoline prices in California without outages and compare the simulated prices to those from by base case simulation (including outages). I then calculated the average differential between the two across all periods in which an unexpected outage occurred at a California refinery. Table 7 lists estimates equivalent to those in Table 8, with the exception that the counterfactual removes all outages as opposed to changing fuel compatibility. For example, the value in the upper left corner of Table 7 is the average price differential in California between months in which a local outage occurred and those same months but-for the outage. The point estimates for the effect of local refinery outages are 6.7, 7.3 and 7.7 cents per gallon for California, Chicago and Milwaukee respectively. This suggests that indeed, local refinery outages in Illinois and Wisconsin over 1995 to 2001 were of greater magnitude than local outages in California.

The estimates in Table 7 provide a way to normalize and compare the estimates of the effect of fuel compatibility across states. Using the calculated magnitude of local outages in California, Illinois and Wisconsin, I normalize the effect of incompatible content regulations from Table 8 by the magnitude of the outage in Table 7. 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 a local outage which could be mitigated if local content regulations were compatible with 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. Regardless, these results imply that price volatility from local refinery outages could be substantially mitigated by content regulation compatible with federal RFG standards, especially in

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simulated prices in the counterfactual.

the case of Illinois and Wisconsin.

The greater degree to which gasoline compatibility mitigates price spikes in Chicago and Milwaukee is consistent with the nature of product differentiation between ethanol-blended RFG, CARB gasoline and federal RFG. In particular, it depends on the extent to which California, Illinois and Wisconsin are geographically differentiated from refineries producing federal RFG. Fuel compatibility only mitigates a supply shocks if transportation costs from refiners producing RFG in other regions are sufficiently low. In either the case of a local outage in Illinois or a local outage in California, the lowest-cost alternative source of federal RFG is Texas and Louisiana. 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 ship by barge to California, incurring higher transportation costs, and, as a result, mitigate less of an outage-based price spike. This indicates that virtually all of the differentiation for Chicago and Milwaukee ethanol-blended RFG is product differentiation. While product differentiation is important for CARB gasoline, geographic differentiation also contributes to price spikes in California.

8.2 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.

8.2.1 Changes in Refinery Concentration

To simulate the effect of changes in refinery ownership, 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 6a) and product formulation (Table 6b). 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 6a and 6b, mean wholesale prices by region are between 0.9 (PADD 3) cents and 1.3 cents (PADD 4) higher with actual refinery consolidation. Consolidation increases wholesale prices on average from 0.7 cpg (CARB gasoline) to 1.5 cpg (Ethanol blended RFG). Thus, the simulation results imply that even with refinery divestitures required as part of mergers, changes in refinery ownership over this period increased prices.

I also estimate the effect of refinery ownership on gasoline price spikes caused by local refinery outages. In Table 9, 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. Contingent on a local outage, industry consolidation has a much larger effect on ethanol-blended RFG (4.6 cpg in Illinois) than on CARB gasoline (0.9 cpg in California). This suggests that refinery ownership consolidation leads to a greater concentration of ethanol-blended RFG production locally, relative to CARB gasoline production.

8.2.2 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%.[41] 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 more in gasoline-importing regions. As above, Tables 6a and 6b present the descriptive statistics for the simulated counterfactual prices by geographic and product market and Table 10 presents the simulated price differential between the counterfactual and the base case, conditional and unconditional on refinery outages.

The results in Tables 6a and 6b 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 10 contingent on a local outage and contingent on no outages are statistically indistinguishable.

8.3 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.

8.3.1 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.[42] Each refiner incorporates these priors into her production choice in the first step of the optimization problem. I constrain the continuum of all possible outages to a discrete subset: single, refinery-wide outages. Given the production choices for each element of

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[41] In 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.

[42] The common ex ante outage probability is consistent in expectation with the actual outages observed over the study period. Numerically, the probability of a refinery-wide outages at each refinery in each period is 0.0021.

the state space (each outage contingency), I identify the initial production choice for each market which ex ante maximizes each refiner's expected profits. I then simulate prices in each market assuming this initial choice is binding, but allowing the refiners to reallocate production in response to the actual refinery outages.

Table 11a and 11b compare descriptive statistics for simulated prices under base case and forward-looking refinery optimization. Simulated mean 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. Conventional, RFG, jet fuel and distillate mean prices are 0.11 cpg lower to 0.07 cpg higher with expected profit maximization than with profit maximization. This is consistent with ex ante expectations - since outages have the greatest effect on CARB and ethanol-blended RFG, incorporating the possibility of outages will increase production of CARB and ethanol-blended RFG more than other products.

When compared to the magnitude of the effect of incompatible regulations, though, the modelling assumption I make has an effect an order of magnitude less that then the effect of incompatible regulations. Several explanations exist for the relatively small magnitude of the effect. First, 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.[43] 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.

8.3.2 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). For each of the sensitivity tests, I bound the coefficients at two standard deviations above and below the NLLS estimate reported in Table 4. Table 12 reports the differential price effect from gasoline content regulations contingent on a local outage. The differentials reported in Table 12 are equivalent to the first column in Table 8. Table 13 reports the percentage of local price volatility mitigated if CARB and ethanol-blended RFG regulations were compatible with federal RFG.

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 pos-

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

itively correlated with demand elasticity. If demand curves are less elastic, a supply shock of similar magnitude has a greater effect on prices. This is consistent with the results in Table 12, in which the estimated effect of content regulations contingent on a local outage decrease as demand becomes more elastic. In either case, though, the estimated proportion of volatility from local outages mitigated by fuel compatibility is relatively close to the results from the NLLS minimizing parameter vector, 69 and 73 percent for California, 90 to 95 percent for Illinois and 89 to 94 percent for Wisconsin. In addition to the testing the sensitivity of the simulation results to demand elasticities two standard errors above and below the NLLS point estimate, I also test the robustness of the simulation results to demand elasticity of -0.23, the median short-run gasoline demand elasticity estimate across the 363 estimates used for meta-analysis by Espey(1998). Again, the results are consistent with the intuition that refinery outages will have a larger effect on prices as demand becomes less elastic.

In general, the other sensitivity results presented in Table 12 are consistent with the ex ante predictions. Two components drive how variations in the estimated parameters affect estimates in Table 12: the incremental production costs associated with the regional content regulations and the degree to which production of the special blend is concentrated at local refineries. As a result, parameters affecting these two factors have the greatest effect on the price differential between the base case and counterfactual simulations. For example, cost coefficients on ethanol-blended RFG and CARB should be positively correlated with the differentials reported in Table 12, since each represents the incremental production costs to refiners. 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 in some sensitivity tests, the percent of the price volatility from a local outage mitigated by content regulations, reported in Table 13, seems fairly robust to changes in the parameters. Across the sensitivity tests, mitigation of local outages varies from 67 to 74 percent for California, 88 to 98 percent for Illinois and 90 to 99 percent for Wisconsin. This suggests that, although the magnitude of the effect of content regulation does vary to a degree, the basic conclusion is robust, 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.

9 Conclusion

In this paper, I use a structural model of refinery production to estimate two effects of regional gasoline content regulations on 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 VIII 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, is 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 increase prices by 1.4 to 1.5 cpg in Illinois and Wisconsin and by 0.73 cents per gallon in California. 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.

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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	Maintenace at crude unit due to acid spill	20-Sep-01	10-Oct-01	7,014	c
OKLAHOMA	Ponca City	Conoco	Removal of 54kbbl/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: Reduced Form Summary Statistics

Variables	Mean	Std. Dev	Min	Max
Gasoline Prices				
DTW Price	79.31	17.81	37.90	151.80
Rack Price	71.99	17.73	34.40	147.90
Retail Price	87.83	18.23	47.40	159.70
Gasoline Volumes				
Conventional Volume	5,319.3	4,640.1	97.4	21,916.1
Oxygenated Volume	2,053.5	2,539.6	0.6	15,720.7
Reformulated Volume	4,746.8	4,996.7	0.9	40,564.6
Content Regulations				
RFG Dummy	0.31	0.46	0.00	1.00
Oxygenated Dummy	0.22	0.41	0.00	1.00
Ethanol Blended RFG Dummy	0.02	0.13	0.00	1.00
Federal Phase 2 RFG Dummy	0.05	0.22	0.00	1.00
Federal Phase 1 RFG Dummy	0.25	0.43	0.00	1.00
CARB Dummy	0.01	0.09	0.00	1.00
Mandatory Ethanol Dummy	0.04	0.19	0.00	1.00
Mandatory Oxygenation Percentage	0.45	0.88	0.00	3.50
Demand Instruments				
State Population (millions)	7.28	7.50	0.63	33.90
Population Density	190.6	252.2	1.1	1,143.7
Per Capita Income (000s)	23.82	4.56	15.22	40.64
Total Licensed Drivers (millions)	3.87	4.03	0.34	22.40
Registered Autos Per Person	0.70	0.10	0.43	0.96
Registered Buses Per Person	0.00	0.00	0.00	0.01
Registered Motorcycles Per Person	0.03	0.01	0.01	0.07
State Tax	19.83	4.99	7.50	39.00
Federal Gasoline Tax	18.36	0.05	18.30	18.40
Cents Per Gallon Tax	38.19	4.99	25.80	57.30
Crude Spot Prices				
Cushing WTI Spot Price	50.50	11.22	26.99	81.95
Brent North Shore Spot Price	46.91	11.23	23.39	78.57

Table 3: Reduced-Form Regressions Results
Dependent Variable: Monthly Average Real Rack Price Net of State and Federal Taxes (cents/gallon)

		Specification	
Variable	**Model 1**	**Model 2**	**Model 3**
CONSTANT	**12.550****	**61.237****	**6.617****
	1.377	0.721	1.428
QUANTITY	**0.00047****	**-0.00058****	**-0.00037***
	0.00015	0.00009	0.00013
WTI MONTHLY CRUDE PRICE	**1.159****		**1.177****
	0.013		0.009
OXYDUMMY	**3.495****	**4.696****	**4.947****
	0.754	0.437**	0.513
RFGDUMMY	**3.839****	**4.065****	**4.238****
	0.552	0.261	0.354
RFGETHDUMMY^	**1.836**	**1.855***	**1.675**
	1.793	0.833	1.118
CARBDUMMY^	**3.184**	**5.646****	**5.050***
	2.036	1.677	1.974
Geographic Dummy Variables	State	State	State
Temporal Dummy Variables	-	Month-Year	State-Month
R-Squared	0.7902	0.9390	0.8722
Estimated Rho	0.615	0.534	0.471

Notes:
* denotes significance at 5% level
** denotes significance at 1% level
^ Both Ethanol requirements for gasoline and CARB gasoline requirements are treated additively to the RFGDUM
(e.g. Holding all else equal, CARB gasoline prices are greater than conventional gasoline prices by the sum of the coefficients on RFGDUMMY and CARBDUMMY.)

Table 4: NLLS Parameter Estimates

Variable	Parameter	Coefficient	Standard Error
Demand Elasticity	epsilon	0.337	0.004
Competition Coefficient	alpha	0.031	0.003
Cost Function Parameters			
Marginal Cost Parameter	beta0	0.436	0.028
Log(Distillation Capacity)	beta1	-0.867	0.023
WTI Crude Price	beta2	0.765	0.008
RFG Dummy	beta3	5.009	0.383
Ethanol-blended RFG Dummy	beta4	8.210	0.737
CARB Dummy	beta5	10.517	0.374
Jet Fuel Dummy	beta6	-1.758	0.209
No. 2 Distillate Dummy	beta7	-3.996	0.179
R-squared (quantities)		0.998	
R-squared (prices)		0.926	

Note: Coefficients jointly minimize NLLS. Solution based on gradient of steepest ascent numerical search algorithm.

Table 5a: 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
Estimated Prices - Reduced Form Model 1							
Mean	70.82	70.42	67.93	70.89	68.48	75.52	76.94
Standard Deviation	16.50	16.89	16.75	17.13	16.71	16.20	16.69
Max	118.94	117.73	116.01	120.73	117.94	123.52	125.96
Min	38.05	36.02	35.55	36.04	34.85	39.86	43.00

Table 5b: 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
Estimated Prices - Reduced Form Model 1						
Mean	70.52	72.69	75.75	82.59		
Standard Deviation	16.87	17.03	17.32	17.85		
Max	124.94	125.96	120.73	125.76		
Min	34.85	39.31	43.36	49.39		

Table 6a: Counterfactual Results - Mean Wholesale Price by PADD

	PADD Region						
Simulation Run	1a	1b	1c	2	3	4	5
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 6b: Counterfactual Results - Mean Wholesale Price by Formulation

	Formulation					
Simulation Run	Conventional	RFG	Ethanol-Blended RFG	CARB Gasoline	Jet Fuel	Distillate
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 7: Simulated Wholesale Price Differential Due to Unexpected Refinery Outages
(cents per gallon, standard errors in parenthses)

	Conditional on Outage Type			
State	Local Outage	Regional Outage	No Refinery Outage	Unconditional
California	**6.68**		**0.07**	**0.85**
	(0.08)		(0.001)	(0.02)
Illinois	**7.28**	**2.38**	**-0.02**	**0.88**
	(0.27)	(0.04)	(0.08)	(0.13)
Wisconsin	**7.72**	**3.47**	**0.00**	**1.46**
	(0.28)	(0.07)	(0.10)	(0.16)

Table 8: Simulated Wholesale Price Differential Due to Fuel Compatibility
(cents per gallon, standard errors in parenthses)

	Conditional on Outage Type			
State	Local Outage	Regional Outage	No Refinery Outage	Unconditional
California	**9.26**		**4.46**	**5.36**
	(0.47)		(0.40)	(0.43)
Illinois	**9.57**	**4.71**	**2.97**	**3.76**
	(0.72)	(0.76)	(0.83)	(0.70)
Wisconsin	**9.92**	**5.01**	**2.86**	**4.17**
	(0.71)	(0.79)	(0.84)	(0.68)

Table 9: Simulated Wholesale Price Differential Due to Refinery Consolidation
(cents per gallon, standard errors in parenthses)

	Conditional on Outage Type			
State	Local Outage	Regional Outage	No Refinery Outage	Unconditional
California	**1.41**		**0.54**	**0.73**
	(0.11)		(0.07)	(0.08)
Illinois	**6.02**	**1.30**	**0.39**	**1.40**
	(0.58)	(0.21)	(0.08)	(0.17)
Wisconsin	**5.45**	**1.11**	**0.65**	**1.54**
	(0.56)	(0.21)	(0.10)	(0.19)

Table 10: Simulated Wholesale Price Differential Due from Five Percent Increase in Refining Capacity
(cents per gallon, standard errors in parenthses)

	Conditional on Outage Type			
State	Local Outage	Regional Outage	No Refinery Outage	Unconditional
California	**3.90**		**4.47**	**4.27**
	(0.51)		(0.29)	(0.32)
Illinois	**3.85**	**4.31**	**3.86**	**3.78**
	(1.27)	(1.08)	(0.18)	(0.18)
Wisconsin	**3.91**	**4.39**	**3.85**	**3.75**
	(1.21)	(1.08)	(0.22)	(0.22)

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.

Table 11a: 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 11b: 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

Table 12: Simulated Wholesale Price Effect Due to Fuel Compatibility Contingent on Local Outage

			Wholesale Price Differential Due to Fuel Compatibility Contingent on Local Outage		
Parameter	Initial Value	Adjusted Value	California	Illinois	Wisconsin
Base Case			9.3	9.6	9.9
Demand Elasticity	-0.337	-0.230	11.0	11.7	12.3
Demand Elasticity	-0.337	-0.329	9.2	9.9	10.2
Demand Elasticity	-0.337	-0.346	9.2	9.3	9.5
Competition Coefficient	0.031	0.0359	9.4	7.8	8.2
Competition Coefficient	0.031	0.0251	9.2	9.3	9.7
WTI Crude Price	0.765	0.780	9.4	9.6	9.8
WTI Crude Price	0.765	0.749	9.3	9.6	9.9
Federal RFG MC Dummy	5.009	5.7753	8.5	8.9	9.2
Federal RFG MC Dummy	5.009	4.2429	9.9	10.3	10.7
Ethanol RFG MC Dummy	8.210	9.685	9.1	10.9	11.3
Ethanol RFG MC Dummy	8.210	6.735	9.3	8.3	8.6
CARB MC Dummy	10.517	11.264	10.0	9.7	9.9
CARB MC Dummy	10.517	9.770	8.7	9.7	10.0

Note: Sensitivity results based on simulations deviating from structural model parameter estimates.

Table 13: Simulated Price Volatility From Local Outage Mitigated By Compatible Regulations

Parameter	Initial Value	Adjusted Value	Percent of Outage Price Volatility Mitigated By Federal-RFG Compatibility California	Illinois	Wisconsin
Base Case			72%	91%	92%
Demand Elasticity	-0.337	-0.230	67%	98%	99%
Demand Elasticity	-0.337	-0.329	69%	95%	94%
Demand Elasticity	-0.337	-0.346	73%	90%	89%
Competition Coefficient	0.031	0.0359	74%	88%	90%
Competition Coefficient	0.031	0.0251	70%	92%	92%
WTI Crude Price	0.765	0.780	74%	94%	93%
WTI Crude Price	0.765	0.749	72%	93%	92%
Federal RFG MC Dummy	5.009	5.7753	70%	91%	92%
Federal RFG MC Dummy	5.009	4.2429	72%	92%	93%
Ethanol RFG MC Dummy	8.210	9.685	70%	91%	92%
Ethanol RFG MC Dummy	8.210	6.735	73%	92%	92%
CARB MC Dummy	10.517	11.264	73%	93%	93%
CARB MC Dummy	10.517	9.770	72%	92%	92%

Note: Sensitivity results based on simulations deviating from structural model parameter estimates.

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

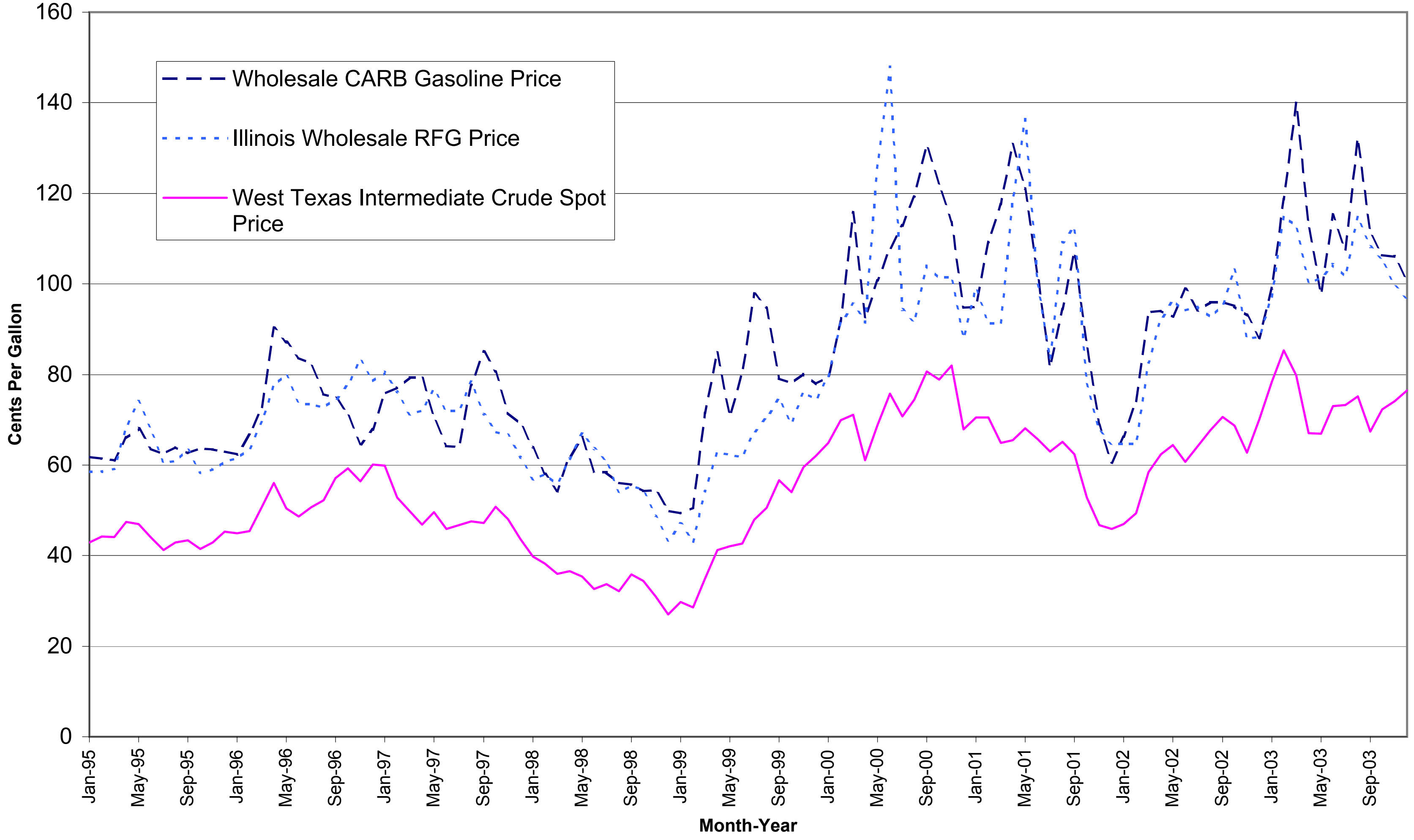

Figure 2: CARB/WTI Spot and IL RFG/WTI Spot Differentials
Jan 1995 - Dec 2003