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Competition in a Network of Markets: The Natural Gas Industry[†]

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ABSTRACT

Federal regulators recently allowed natural gas pipelines to offer transmission services to their customers. Pipelines previously were *merchant carriers* that were required by regulatory decree to own the gas they transported. Now, pipelines can voluntarily choose to function as pure transportation firms (*contract carriers*) and their customers can use transportation to buy gas from suppliers connected to the pipeline network. A major aim of this research is to determine the extent to which pipelines have become interconnected transporters of gas and how competition works in an interconnected transmission network. The institutions created by market participants and the transactions that they now can make are examined in detail. Monthly and daily spot gas field prices are examined. The empirical results lead to the conclusion that pipeline transportation created a national market for natural gas.

Draft -- Comments Welcome

December 1991

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The price of a commodity "tends to uniformity" for one reason: the buyers at point B refuse to pay more than the price at point A plus transportation, and the buyers at A act similarly. Or the sellers act in this manner."

George Stigler (1966, p. 85)

And the shipper who earns his living from using otherwise empty or half-filled journeys of tramp-steamers, ..., or the arbitrageur who gains from local differences of commodity prices, are all performing eminently useful functions based on special knowledge of circumstances of the fleeting moment not known to others.

F.A. Hayek (1945, p. 522)

1. Introduction

For over forty years, public authorities substituted direct price and service regulation for markets in the natural gas industry. Traditionally, regulation has been deemed necessary to prevent market failure in industries characterized as natural monopolies.[1] This view that the natural gas industry is subject to market failure has never been tested. Regulators cannot perform controlled experiments to see how a market might function, because many natural monopolies are public

[1] Certain industries are held to be natural monopolies because, " advantages to large scale firms are such that unrestricted competition would lead to exclusive occupancy of individual markets by one or a very few firms, with greater efficiency and monopolistic pricing tendencies both resulting. These effects may include inferior service." Bain (1968, 581).

F.M. Scherer states in his classic industrial organization text that, "Reasonably clear examples [of natural monopoly] include electric power generation and gas distribution, local telephone service, railroading between pairs of small to medium-sized metropolitan areas, and the long-distance transportation of petroleum and gas in pipelines." (1980, p. 482) utilities. The value that regulators place upon service reliability in such industries is paramount. The fear of market failure, and the resultant possibility that service to customers could be curtailed, makes deregulation a risky proposition from the regulator's point of view. Natural gas pipelines provide a stark example where the curtailment of service could cause customers to suffer grave consequences, especially on a cold winter's night.

Federal regulators recently allowed natural gas pipelines to offer different types of transportation services to their customers. Historically, pipelines functioned as merchant carriers by regulatory decree. Now, most major natural gas pipelines have changed from private merchant carriers to contract carriers. As merchant carriers, the pipelines purchased gas upstream in the producing fields and sold it in downstream markets. Now, as contract carriers, pipelines provide pure transportation services to their customers. The deregulation of pipeline transportation resulted from the need to mitigate the effects of previous regulatory errors rather than from a conscious decision to change the way pipelines are regulated (Teece and Dirrheimer, 1989; Smith et al. 1987).

The institutional change in pipeline carrier status transformed the natural gas commodity and transportation markets so that they can no longer be characterized as natural monopolies. Gas market participants now can reach through the transmission grid to transact at all directly or indirectly connected nodes. The previously separate markets have now become integrated into one large network market. These markets now function much like other commodity markets.

In the following sections, I present an overview of the natural gas industry under the old regime of merchant carriage. The new market environment and trading institutions that developed in response to regulatory change are developed in detail. Preliminary hypotheses are made about the effects of these changes on the behavior of natural gas prices. Two data sets are examined to determine if and how the relationship between gas prices across regions has changed and how they now behave. The hypothesis that relative prices in the network are such that all arbitrage opportunities are fully exploited is tested using daily spot price data for alternative pipeline network topologies.

2. Institutional Background

There are three main sectors in the natural gas industry: production, transmission and distribution. Natural gas pipelines are the middlemen between the production and the distribution sectors. As such, they could provide several alternative types of transmission service: merchant or private carriage, contract carriage, or common carriage.[2]

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[2] Transportation firms are classified by the type of service they provide their customers. Merchant carriers transport only commodities that they own. Contract carriers transport, under specific agreement, commodities that belong to their customers. Common carriers offer to serve the general public indiscriminately (Daggett, 1955).

A. Merchant Carriage

Firms in the natural gas industry initially organized vertically into all three sectors during the 1930's. During this time, the Federal Trade Commission (FTC) had been studying the practices of holding companies in both the electric and gas industries. The FTC recommended that the natural gas industry be regulated as a public utility. Subsequently, Congress passed the Natural Gas Act (NGA) of 1938 which placed pipelines under the regulatory purview of the Federal Power Commission (FPC), and its successor agency, the Federal Energy Regulatory Commission (FERC).

Under the NGA, pipelines were made private merchant carriers.[3] Congress organized the natural gas industry as a system of separate merchant carrier pipelines to prevent the perceived market failures of the other forms of organization they considered. Congress considered mandating common carrier status on pipelines, but pipeline industry advocates were able to dissuade this legislation. "...pipeline companies viewed the industry as an integrated whole since they designed a sale as a complete unit. Customers had to be assured an adequate supply of gas even on the coldest day." (Mogel and Gregg, 1983, pp. 20-21)

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[3] The FPC imposed cost regulation on the pipelines that discouraged them from owning their producing fields. This caused the production and transmission sectors to become organized through long term contracts instead of vertical integration because pipelines were not allowed to earn a rate of return on gas they produced. The Public Utility Holding Company Act of 1935 made separate firms provide distribution and transmission. Mulherin (1984, 1986) discusses how federal regulation caused the industry to become organized through long term contracts.

Under the system of merchant carriage, pipelines were required to *own* the gas they transported. In other words, pipelines were required to tie the sale of gas to its transportation. Pipelines could not offer pure transportation to their customers. Pipeline customers, usually local distribution companies and large end users, could purchase only the bundled package of services that included gas acquisition, storage and transmission. Two qualities of bundled service were offered, interruptible and firm (uninterruptible).

The process through which federal regulators certificated pipeline construction led to a dense and disconnected network of pipelines. Individual pipelines were constructed sequentially as new supplies were found and as the demand for natural gas increased. The Federal Power Commission certificated the construction of a new pipeline only after the pipeline had shown that it had sufficient reserves to supply its downstream customers for a period of 15 to 20 years. To this end, pipelines entered long term purchase contracts with producers under which the reserves in the gas wells were dedicated to the pipeline.[4] Pipelines could not be abandoned, and contracts could not be renegotiated without the approval of the FPC. Through the certification process, the pipeline system became dense with numerous crossings (but not interconnections) of pipelines that purchased gas in different fields and sold it in different downstream markets.

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[4] There are several other explanations for the use of long term contracts between natural gas producers and pipelines. See Mulherin (1984, 1985), Hubbard and Weiner (1991) and Masten and Crocker (1985, 1991).

An example can illustrate the development of the pipeline system more clearly (see Figure 1). Suppose that gas field 1 is discovered. Firm 1 wants to construct a pipeline to sell this gas to demanders at market 1. To obtain regulatory approval to construct the pipeline, firm 1 enters long term purchase contracts with producers in field 1. Under these contracts, the gas is dedicated to pipeline 1 and cannot be sold to another pipeline without regulatory approval. Later, and through the same procedure, pipeline 2 (3) is constructed to buy gas at field 2 (3) and sell it in market 2 (3). The resulting network is unconnected, although there are pipeline crossings. In addition, this organization required greater capacity relative to throughput because gas flows could not be reallocated through the pipeline network.[5]

Each gas field to which a pipeline connected was essentially a separate market from the fields that connected to other pipelines. Because each pipeline was separate, gas could not flow to the customer who valued it most. Gas could flow only to customers on the pipeline connected to the producing field. Under such an arrangement, prices in gas fields could not accurately reflect the value of the resource at other locations. Federal regulators created a system with one downstream market, one field market, and one pipeline. Because of this balkanization of the industry, natural gas prices could not be equalized across all fields and downstream markets. The price of gas at one location did not correctly

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[5] The integration of several small markets into one large network of markets creates gains due to economies of massed reserves (Mohring, 1976).

signal the marginal value of natural gas at other locations. There was an inefficient allocation of gas.

B. Unanticipated Events and Pipeline Deregulation

Despite regulation which attempted to maintain high levels of reliability to the users of natural gas, there were natural gas shortages in the 1960's and 1970's.[6] In response to these shortages which were caused by federal price controls, Congress passed the Natural Gas Policy Act of 1978 (NGPA). The NGPA deregulated the field price of most gas in steps and completely deregulated some types of gas.[7] Pipelines entered into long term contracts to purchase large volumes of gas at this time to prevent the future curtailment of service to their customers and in fear of an increase in the price of gas. The purchase contracts contained high minimum purchase provisions and high prices because much of this gas was recently deregulated under the NGPA.

After these contracts were signed, gas demand fell due to declining oil prices and mild winter weather conditions. Pipelines faced large minimum purchase obligations of high priced gas as their sales declined. Many pipelines renegotiated their contracts with producers and agreed to transport the gas on

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[6] See MacAvoy and Pindyck (1975) for a discussion of the effect of the FPC's wellhead price regulation on the natural gas shortage.

[7] See EIA (1988) for a discussion of prices of various categories of gas under the NGPA.

behalf of the new buyers. In response to increased demand for transportation by gas users, the FERC authorized transportation of customer-owned gas.

The FERC approved transportation transactions individually.[8] Then, in October 1985, the FERC issued Order 436 which allowed interstate pipelines to provide pure transportation under "blanket certificates." This Order formally distinguished and separated pipelines' merchant and transportation functions. After some initial skepticism, pipelines began to make application to become "Open Access" pipelines. Figure 2 shows the cumulative number of pipeline applications and approvals for Open Access status.

Pipelines continue to provide their traditional service of bundled gas and transportation, although an increasing share of total pipeline throughput consists of customer-owned gas. Between 1982 and 1987, the transmission of pipeline-owned volumes decreased by 60% and the transmission of customer-owned volumes increased by 180% (EIA, 1989). Transportation as a separate service accounted for two-thirds of all interstate gas movements by 1987, and by 1991 over 85% of pipeline shipments were customer-owned (FERC MegaNOPR, 1991). Figure 3 shows, by user category, the volumes of customer-owned gas transported by interstate pipelines.

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[8] Much of this gas was sold to price sensitive industrial users who otherwise would have switched to alternative fuels. These "Special Marketing Programs" were ruled to discriminate illegally against certain classes of customers in *Maryland People's Counsel v. FERC*, 761 (DC Cir., 1985). The FERC subsequently issued Order 436.

C. Contract Carriage and New Market Institutions

Downstream gas demanders now may purchase gas directly in the spot market and purchase separately the transmission of their gas through the pipeline system. Gas users in each downstream market can purchase from all the fields to which they are directly or indirectly connected. If the prices across fields are disparate, gas purchasers will demand transportation connections to gain access to gas in fields with low prices. Gas producers in fields with low prices will demand transportation connections to gain access to customers in downstream markets with high prices. When new pipeline interconnections are made, gas can flow to those customers who value it most highly.

Under merchant carriage, gas users bought from the pipeline either an interruptible supply of gas or a firm (uninterruptible) supply up to some maximum daily volume, the "callable" volume. The FERC allowed customers who held firm purchase agreements with the pipeline to convert voluntarily the callable volume to uninterruptible transmission rights. These well-defined transmission rights facilitate the efficient allocation of guaranteed transportation to those shippers who value it most.[9] The pipeline customers who hold these rights, usually large utilities, may use their transmission capacity to ship their own gas or they can sell all or part of their capacity to a third party.

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[9] See Smith, De Vany and Michaels (1990) initiate the discussion on the efficiency improvements made possible by defining exchangeable transportation rights.

Holders of transmission capacity have no incentive to hoard it because the tariff that they pay consists of two parts. There is a reservation charge and a volumetric charge. The reservation charge depends only on the volume of gas for which uninterruptible transportation is reserved. The volumetric charge is the amount paid per unit of gas that is physically shipped.[10]

Unused firm transmission capacity is sold by the pipeline as interruptible transportation. Pipelines obtain capacity utilization information by monitoring throughput. The unused capacity is posted for sale on electronic bulletin boards in real time. These bulletin boards are accessible by all market participants who may purchase the capacity.

Pipelines coordinate their customers' transmission demands during what is called "bidweek." During the bidweek, usually the third week of each month, pipeline customers nominate the volumes they would like to ship during the following month. These nominations specify the injection point, the withdrawal point, and the volume of gas to be shipped. Customers can nominate volumes only up to the amount of their firm transmission rights. Those pipeline customers

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[10] For each pipeline, the FERC sets a cost based transmission tariff from which the pipeline may discount selectively. The actual tariff charged equalizes between alternative pipelines on the same route. Pipelines with high regulated tariffs discount to the level of pipelines with lower tariffs. In this way, historical accidents that affect tariffs through cost accounting procedures are not binding constraints. Through flexibility in the price of transmission, pipelines compete for throughput within corridors and between corridors (See *Oil & Gas Journal*, December 10, 1990, pp. 33-39).

who resell their transmission capacity to third parties are responsible for nominating and paying for it.

During the bidweek, many of the gas users with capacity rights purchase the volumes for which they nominate transmission. The spot contracts they enter are for volumes to be delivered to a specific injection point on the pipeline system. From this point, they exercise their transmission right and withdraw the gas from the pipeline at the downstream destination. The duration of these spot contracts usually is thirty days or less. The average transaction price of these spot contracts executed during the bidweek is called the "bidweek price."

As a point of reference, most gas traders rely on the price quotes published by the industry periodicals. Figure 4 shows the number of nodes for which the *Gas Daily* reported bidweek prices from April 1987 to December 1990. The bidweek price is used by some gas sellers to index prices in longer term sales arrangements. However, gas traders rely on the information reported in the daily price surveys for the previous day. In fact, traders often call the industry periodicals that take price surveys to compare prices before they close a deal. Frequently, in return for this real time information service, the traders will call back after they have closed a spot deal to report the price.[11]

Brokers buy and sell gas throughout the pipeline network, although they do not have uninterruptible transmission rights of their own. They aggregate the

[11] This information was obtained from personal conversations with editors and reporters of the *Gas Daily*.

supplies of producers and the demands of gas users. By purchasing interruptible transmission from the pipeline, they can ship gas from the producers to the users. Essentially, brokers hold a portfolio of gas market transactions which they match in real time. Some brokers act as the purchasing agent for downstream local distribution companies. These brokers use the customer's transmission capacity to deliver the gas which they sell to the customer.

3. Trading Strategies and Preliminary Ideas

With the institutional framework described above now in place, several questions arise: What types of exchanges can be made in this market? Does the presence of a directional physical distribution system preclude efficient operation of the gas spot market? How might the behavior of prices across nodes in the network change once pipelines become contract carriers? In this section, the transactions that traders in this market can execute are examined and preliminary hypotheses are formulated.

Gas producers and end users arbitrage in their purchasing decisions. Producers attempt to maximize the price they receive for gas at the point where it enters the pipeline. Similarly, gas users attempt to minimize the delivered price they pay for gas. Gas brokers serve as the market makers and exploit price disparities. Gas brokers are the arbitrageurs in the transmission network. They exploit nonequilibrium price differences in several ways, even if this means selling downstream gas upstream. The types of deals that gas market traders can execute are best illustrated by example.

Consider the pipeline network shown in Figure 5. There are four producing fields, A through D, two end user markets, 1 and 2, two Brokers, X and Y, and one pure interconnection node, I. The end users in downstream markets will shift purchases to minimize the delivered price they pay for natural gas. Some of these end users will purchase gas from producers directly. Others will purchase it from brokers.

Suppose initially that the network is in equilibrium, meaning that the differences between prices at different nodes are equal to the cost of transmission.[12] Now, let there be an exogenous increase in the demand for gas in Market 2 which increases its price. Brokers, or the end users themselves, will purchase gas upstream and ship it to this downstream market until the price difference between the nodes is just equal to the price of transmission.

Consider a more complex trade. Again, starting from equilibrium, suppose that the price of gas at Field B is too high relative to the price at Field A.[13]

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[12] Formally, arbitrage does not lead to a single equilibrium vector of prices. Rather, it allows us to place a bound on the disparity in relative prices (cf Huang and Litzenberger, 1988, pp. 106-109). Throughout this discussion, the term equilibrium refers to a set of prices such that the transmission network is free of arbitrage opportunities.

[13] To see that the prices could be out of equilibrium, take Market 1 as the base node and convert prices to this common node. The price of Field B gas, P_B, in Market 1 would be P_B plus the price of transmission, t(B,1): $P_{B,1} = P_B + t(B,1)$. Similarly, the price of Field A gas in Market 1 would be $P_{A,1} = P_A + t(A,1)$. If $P_{B,1} - P_{A,1} \neq 0$, then this price spread represents an arbitrage opportunity.

None of the market participants has transmission rights to send gas against the flow of the pipeline from A to B. Brokers, acting individually or in concert, can exploit this opportunity. Suppose that a broker is currently purchasing gas at node B and selling it in Market 2. This broker can buy gas at node A, ship this to his customer in Market 2 instead of the gas he owns at node B. To complete the trade, the broker then can sell the gas at node B that he shipped to Market 2. Brokers will continue to rearrange the transactions in their portfolios in this manner until nonequilibrium price spreads dissipate. Thus, even seemingly impossible transactions which involve selling downstream gas upstream can be executed.

The gas brokers sometimes take no net position in the gas commodity market, but arrange transactions between buyers and the sellers. By matching buyers and sellers, the brokers earn a fee and cause arbitrage opportunities to dissipate. Brokers also can aggregate unused transmission capacity, and can be compared to freight forwarders. In these ways, they can exploit intertemporal arbitrage opportunities and can contest the markets through contracts.

Through their trades, brokers reveal information about the relative value of gas at other locations, and market prices at each node will contain this information. The price of gas at any node will reflect the marginal value of gas throughout the network of markets.

4. Empirical Methodology

This section discusses several alternative ways that the price data will be analyzed to test the arbitrage arguments made above.

A. The Market Test

Stigler and Sherwin (1985) show that under certain assumptions the correlation between two price series is the critical statistic in determining whether they are generated in the same market. They define the market as "the area within which price is determined."[14] If two trading places are in the same market, then traders will exploit nonequilibrium price differences in a fashion like that described in the examples above. If transport costs are stable, then price spreads should remain stable even as price levels fluctuate. As a consequence, the variance in the price spread will be much smaller than the variance in the average price. The ratio of these variances is summarized entirely by the ratio $(1 - \rho)/(1 + \rho)$ where ρ is the correlation coefficient.[15] If the separate

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[14] (Stigler and Sherwin, 1985, p.555).

[15] Stigler and Sherwin's (1985) market test is the following. Suppose that the price in region i, P_i, is a random walk so that $P_{i,t} = P_{i,t-1} + e_{i,t}$, where $e_{i,t}$ has zero mean and constant variance. The price in region j is also a random walk so $P_{j,t} = P_{j,t-1} + e_{j,t}$. If the two regions are in the same market, then traders will exploit nonequilibrium price differences causing them to dissipate. As a result of this, it should be observed that the variance in the price spread, $Var(P_{i,t} - P_{j,t})$, should be small relative to the variance of the average price or sum of the prices, $Var(P_{i,t} + P_{j,t})$. If we let the variance of $e_{i,t}$ equal the variance of $e_{j,t}$, and let their correlation be equal to ρ, then their ratio $Var(P_{i,t} - P_{j,t})/Var(P_{i,t} + P_{j,t}) = (1 - \rho)/(1 + \rho)$ for a finite time horizon.

producing areas have converged to become one market, then we should observe a high correlation between prices in different regions which implies a low ratio $(1 - \rho)/(1 + \rho)$.

B. Relative Price Variation

If the price spreads across the transmission network are stable, then the dispersion of prices as measured by the variance or standard deviation will also be stable. Price spreads are caused by the price of transmission. As long as the price of transmission between pairs of nodes remains constant, the price spread should remain constant if traders really can and do cause nonequilibrium spreads to dissipate.[16]

C. Testing for Arbitrage Opportunities

When traders transact, they cause the price of gas at each location to reflect its value at each other node throughout the network. If prices at each node reflect all information in the network at each point in time, and all arbitrage opportunities have been fully exploited, then the price of gas at each node should be the best predictor of the following day's price.

For example, let $p_{i,t-1}$ and $p_{j,t-1}$ represent the price of gas at nodes i and j at time t-1. If $p_{i,t}$ is predicted better by $p_{j,t-1}$ than by $p_{i,t-1}$, then there is an

[16] It should be noted that this is the only test used here that assumes that transmission tariffs remain in constant proportion across alternative pipelines.

unexploited arbitrage opportunity between the two nodes. This relationship between relative prices could not exist if the network were fully arbitraged; an arbitrager would exploit the difference in relative prices and cause it to dissipate.

A formal way to model this is that, if prices are consistent with an arbitrage-free equilibrium, the price at each node follows a random walk. Let $i \in N$ index the nodes in the network. Let ϵ_t be a white noise process that may be contemporaneously correlated across nodes, and let W_t represent an exogenous factor that affects the prices at each node, such as the weather. The model can be written as the following system of equations.

$$
\begin{aligned}
p_{1,t} &= \omega_1 W_t + p_{1,t-1} + \epsilon_{1,t} \\
p_{2,t} &= \omega_2 W_t + p_{2,t-1} + \epsilon_{2,t} \\
&\vdots \\
p_{N,t} &= \omega_N W_t + p_{N,t-1} + \epsilon_{N,t}
\end{aligned}
\qquad (1)
$$

The equations can be rewritten by taking first differences, where $\Delta p_{i,t} = p_{i,t} - p_{i,t-1}$. Doing so, each of the resulting time series, the $\Delta p_{i,t}$, is the sum of the exogenous factor W_t and the white noise process ϵ_t :

$\Delta p_{i,t} = \omega_i W_t + \epsilon_{i,t}$.

There are two dimensions in which to test the no-arbitrage opportunities hypothesis: over time and across the network. For the hypothesis not to be rejected, the first difference of price at each node in the network cannot depend on the past price differences for that node, or for any other node. Let $l \in [1, L]$

denote the temporal lag of a variable. The Arbitrage-Free hypothesis can be tested by estimating the following system of equations.

$$
\begin{aligned}
\Delta p_{1,t} &= \omega_1 W_t + \gamma_{1,0} + \sum_{l=1}^{L} \sum_{i=1}^{N} \gamma_{i,l} \, \Delta p_{i,t-l} + \epsilon_{1,t} \\
\Delta p_{2,t} &= \omega_2 W_t + \gamma_{2,0} + \sum_{l=1}^{L} \sum_{i=1}^{N} \gamma_{i,l} \, \Delta p_{i,t-l} + \epsilon_{2,t} \\
&\;\;\vdots \qquad\quad \vdots \qquad\qquad\quad \vdots \\
\Delta p_{N,t} &= \omega_N W_t + \gamma_{N,0} + \sum_{l=1}^{L} \sum_{i=1}^{N} \gamma_{i,l} \, \Delta p_{i,t-l} + \epsilon_{N,t}
\end{aligned}
\tag{2}
$$

This equation implies equation (1) if all of the γ are zero. If one of the γ is nonzero, say $\gamma_{2,1}$ in the first line of equation (2), then this indicates that the price change at node 2 during the previous time period can predict the current price change at node 1. A trader could exploit this predictability by buying gas at one node and selling it at the other. In the formulation above, the test for arbitrage-opportunities is across N nodes for each of L lags. Testing the Arbitrage-Free hypothesis is equivalent to testing the joint hypothesis that all of the γ are equal to zero. If all of the γ are insignificantly different from zero, then equation (2) reduces to equation (1).

5. Data Description

This study utilizes two separate data sets. The first data set contains average regional spot gas prices for the period 1984-89. These data reveal the behavior of gas prices throughout the transition from merchant carriage to contract carriage. The second data set is more disaggregate. It contains gas prices at specific injection and withdrawal points in the transmission network for July 1987 to December 1990. The disaggregate data reveal in detail the behavior of gas prices after pipelines became contract carriers and allow testing of the Arbitrage-Free hypothesis.

A. The "Regional" Data

The regional data were constructed by the Energy Information Administration (EIA). These data consist of monthly observations of the average spot price paid for natural gas in dollars per thousand cubic feet ($/Mcf) in five regions: Appalachia, Louisiana, Oklahoma, the Rockies and Texas. The EIA constructed these data by averaging the spot price reported in each region by several industry periodicals.[17] This procedure enabled the EIA to construct the regional series even when not all sources reported a price. Aggregating these disparate price series increases the noise in the data and biases the results away

[17] Each region's spot price is the arithmetic mean of spot prices reported within that region in the following industry publications: *Gas Daily*, *Gas Price Reports*, *Foster Natural Gas Report*, *Gas Price Survey*, *Natural Gas Intelligence*, *Inside FERC*, *Natural Gas Week*, and *Inside Energy* (Energy Information Administration, 1989).

from finding significant relationships among prices. The primary benefit of aggregation is that it allows the construction of a longer time series of prices which are measured consistently. However, it is also true that individual reporting errors are less likely to influence significantly the empirical results because the data are a composite measure.

B. The "Network" Data

The second data set analyzed in this study was obtained from the *Gas Daily*. This industry publication now reports the price paid for natural gas at over fifty pipeline interconnection nodes within the transmission network. The interconnection nodes are located either where smaller pipelines feed gas from the producing fields to the major "trunk" pipelines, or at the interconnection of several "trunk" pipelines.

Twenty-five nodes were selected at which the *Gas Daily* continuously reported bidweek prices since February 1988. Twenty nodes were selected at which daily spot prices were reported continuously since July 1987. These nodes are located within six geographic areas: West Texas, East Texas, North Texas, South Texas, Oklahoma, and the Louisiana Onshore region. Thirteen of the major interstate pipelines are represented; these pipelines account for the majority of the gas flowing through interstate pipelines (EIA, 1989). Table 1 lists the nodes by region and pipeline company. The major pipeline corridors that connect the producing areas to consuming areas, and to each other, are shown in Figure 6.

TABLE 1 ABOUT HERE

FIGURE 6 ABOUT HERE

The large squares on the map of the national pipeline network (Figure 3) locate and identify the six major pooling areas or hubs. Within each of these areas is a network of pipelines. Figure 7 and Figure 8 show the location of the pipelines in the Louisiana Onshore and the West Texas market areas.[18] These figures demonstrate the density of the transmission grid.

FIGURE 7 ABOUT HERE

FIGURE 8 ABOUT HERE

The "bid week" prices reflect the weighted average price of gas purchased based on volumes and prices for spot deals struck during the bidweek. The daily spot prices are a weighted average of each day's trades. These data are based on prices for injection into the pipeline at the node for which the price is listed.[19] The prices include any gathering and transportation fees incurred to get the gas to the points for which prices are reported. All of the price data used here are based on dry packages[20] of five million cubic feet per day (CFD). The prices

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[18] The detailed pipeline maps shown as Figures 7 and 8 were taken from a FERC (1991) working paper.

[19] For example, the price paid for natural gas injected into the Columbia Gas Transmission pipeline in Erath, Louisiana.

[20] Dry gas is natural gas which has been processed to ensure that all of the liquid petroleum products and other impurities are removed from it.

are on a dollar per million Btu ($/MMBtu) basis for spot contracts of 30 days or less.

6. Empirical Results

A. Results for the "Regional" Data

A time series plot of the regional spot prices demonstrates clearly a pattern of prices that changed over time (see Figure 9). Without any *a priori* information concerning the process that generates the price series, it is clear that the data follow three distinct patterns over three successive time periods: 1984-85 when the prices move independently, 1986-87 when all price movements are small, and 1988-89 when each series moves in step with every other series. Examine the 1984-85 period during which pipelines were disconnected sellers of bundled gas and transportation. In the summer of 1984, the price of gas in Appalachia fell while the price in the Rockies rose, and during the following winter the price rose in Appalachia and fell in the Rockies. Even the prices in Louisiana and Texas, the two regions connected with the most dense grid of pipelines, do not move together during 1984.

By the end of 1986, after Open Access began, gas prices in each region realigned and the new relative prices appear to be stable with each series declining at a similar rate. Since 1987, spot prices in all regions move with remarkable similarity.

FIGURE 9 ABOUT HERE

To quantify how price movements in different regions are related to one another, the Pearson correlation coefficient is calculated between each pair of price series for three successive time periods: 1984-85, 1986-87, and 1988-89. Because the series have a high degree of positive first order serial correlation,[21] the estimated correlation overstates the true correlation because each series follows a similar stochastic process. Therefore, first differences of the price series are used for correlation analyses. Because prices could appear to be correlated even if each region's price responded independently to a common demand shock, all prices are made orthogonal to a seasonal demand variable before the correlation coefficients are calculated.[22]

To test whether the correlation between regions has changed between time periods, Fisher's r to Z transformation is employed. Let r_{xy} be the sample correlation between x and y and let ρ_{xy} be the population correlation between x and y. Then $Z = ½ \ln((1 + r_{xy})/(1 - r_{xy}))$ is approximately normally distributed with expectation $E[Z] = ½ \ln((1 + \rho_{xy})/(1 - \rho_{xy}))$ and variance $Var[Z] = \{(1/(n - 3)\}^{\frac{1}{2}}$ where n is the number of observations used to compute the correlation coefficient (Hays, 1973). The hypothesis that the correlation is

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[21] The price series exhibit high first order serial correlation (Appalachia = .956, Louisiana = .978, Oklahoma = .972, Rockies = ..981, Texas = .983). All subsequent statistical analyses are performed with first differences to remove the serial correlation, although Figures are shown in levels. The reported results are qualitatively the same whether we use prices in levels or first differences.

[22] The seasonal demand variable used is average U.S. population weighted heating degree-days. Heating degree-days are deviations of the mean daily temperature below 65°F.

equal between two independent samples of size n_1 and n_2 can be tested by computing the test statistic $(Z_1 - Z_2)/s_{12}$ where $s_{12} = \{1/(n_1 - 3) + 1/(n_2 - 3)\}^{\frac{1}{2}}$. This test statistic follows a standard normal distribution.

TABLE 2 ABOUT HERE

Table 2 reports the correlation for each region-pair for 1984-85, 1986-87 and 1988-89, and also lists the value of the test statistic for the hypothesis of no change in correlation between the first and last period. The correlation between prices increased significantly for each region-pair. This supports statistically the graphical evidence of Figure 9. These results support the hypothesis that these five regions all functioned separately as distinct markets in 1984-85, but evolved over time into one large market.

The core of Stigler and Sherwin's market test is that nonequilibrium price spreads cannot survive between regions in the same market. If the results of the correlation analysis above are correct, and the five separate markets did converge to one large "network market," then each price spread should become less volatile. Tables 3a and 3b show the spread in prices and associated descriptive statistics for each region-pair for 1984-85 and 1988-89, respectively. For each region-pair, the range of the spread (the maximum spread minus the minimum spread) decreased and the standard deviation of the spread also decreased. In some cases the magnitude of the average price spread increased, such as the spread between Appalachia and the Rockies, but this new spread was more stable.[23] The range

[23] See the first row of Table 3a and Table 3b.

of price spreads and its variance between each pair for Louisiana, Oklahoma, and Texas decreased markedly.[24] The fact that price spreads became more stable confirms the results from the correlation analysis.

TABLE 3A & 3B ABOUT HERE

FIGURE 10 ABOUT HERE

The extent to which prices across regions converged through time can be measured by the variance of prices across the different regions. The variance is calculated across the regions which are in close proximity: Louisiana, Oklahoma, and Texas. Figure 10 plots the level of price dispersion between these regions over time. The substantial decrease confirms our expectations. These regions of high pipeline density quickly became interconnected after pipelines became contract carriers. The low and stable variance of price across these regions supports the argument that the law of one price now holds because prices are disciplined by arbitrage.

B. Results for the "Network" Data

1. Correlation

Each price series was adjusted by a seasonal demand measure before the correlation coefficients were computed.[25] Table 4 shows the correlation between bidweek prices at each node for 1988. The correlation between each

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[24] See the last three rows of Table 3a and Table 3b.

[25] See *supra* footnote 22.

region pair is high, but there are some patterns to be noted from the table. Prices are more highly correlated between nodes in the same region than between nodes in more distant regions. This is most noticeable when comparing correlations between the prices paid for gas in West Texas with the prices paid at nodes in other regions. For example, the correlation between bidweek prices on the ANR pipeline in North Texas and the El Paso pipeline in West Texas is 0.79. By comparison, within North Texas the lowest correlation with the ANR pipeline is 0.97, on the Northern pipeline. Also note that prices on pipelines in Oklahoma are less correlated with those on pipelines in South Texas than for most other regions. These results show that in 1988 prices were more highly correlated between nodes in close proximity than to more distant nodes.

TABLE 4 AND TABLE 5 ABOUT HERE

Correlations for 1990, shown in Table 5, are very high between nodes in the same region and between nodes in other regions. The increase in correlation is particularly noticeable between those nodes on pipelines in West Texas with nodes on pipelines in other regions. The correlation between ANR in North Texas and El Paso in West Texas is now 0.93. Compare this to 0.95, the lowest correlation with ANR in North Texas. Now the correlation between nodes located in South Texas and Oklahoma is much higher, about .98. The correlation between prices at nodes in close proximity has approached the correlation between prices at more distant nodes.

The most brief way to summarize the increase in correlation between more distant nodes in the later time period is to compute the condition number for each correlation matrix. This is the ratio of the largest characteristic value to the smallest characteristic value. The condition number measures directly the collinearity of the columns in the correlation matrix (Greene, 1990). A high condition number indicates high collinearity. The condition numbers for 1988, 1989, and 1990 are 7.03×10^{16}, 1.43×10^{18}, and 2.28×10^{22}, respectively. The increasing condition numbers indicate that the correlations are becoming more equal between all pairs of nodes. The interpretation is that the pressure of arbitrage has become as strong for circuitously-connected nodes as for well-connected nodes.

2. Relative Price Variation

Figure 11 shows the standard deviation of bidweek prices across nodes within each region.[26] Generally the standard deviation in prices within each region is small in magnitude, on the order of 1 to 5 mills. It increases in the winter months when prices rise. The change in price dispersion could be caused by changes in transmission tariffs on certain pipelines. The magnitude of price variation within these regions appears to be economically insignificant in any case.

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[26] The price dispersion is shown as a standard deviation so the units can be interpreted as dollars per million Btu. Units of variance, $\$^2/MMBtu^2$, are difficult to interpret.

FIGURE 11 ABOUT HERE

Note that the patterns of increased price dispersion are similar in different regions. In particular, compare the patterns and magnitudes in Louisiana, East Texas and South Texas. Many of the same pipelines serve these three regions, originating in South Texas, continuing through East Texas and Louisiana up to the northeast. The similar pattern of price dispersion in each region may result from different maximum tariffs charged on each of these pipelines during peak demand periods.

FIGURE 12 AND FIGURE 13 ABOUT HERE

The standard deviation of daily spot prices across all nodes is shown in Figure 12. Generally, it is much more volatile during 1987 than in the following periods. However, during the winter of 1988 prices at some nodes increased dramatically, causing the spike shown on the graph. After this period, the standard deviation appears quite stable. The period between February 1989 and November 1990, the relatively flat period, is plotted with an expanded scale in Figure 13.[27] Price dispersion does increase in the winter months, but the magnitude of the increase appears to be of little significance. The stability of the variance across regions shows that prices move together so that the spread between them is nearly constant.

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[27] The scale of the ordinate has been increased about forty fold.

3. Testing for Unexploited Arbitrage Opportunities in the Network

Each daily price series was tested for nonstationarity using the unit root test developed by Dickey and Fuller (1979) and MacKinnon's (1990) Monte Carlo generated critical values. Because the results of this test are sometimes sensitive to the specification of the testing equation, the test was run using several different lag lengths. The null hypothesis of a unit root could not be rejected for any of the price series. Also, the hypothesis that the differenced price series are nonstationary was rejected. That is, the price series are not integrated of an order greater than one.

The vector autoregression model in (2) was estimated for four different network topologies. The first two topologies, listed in Table 6 as networks 1 and 2, consisted of one node from each of the major pipeline interconnection areas shown in Figure 6. In network 1, the nodes are on different pipelines in each region. In network 2, four of the nodes are on the same pipeline company's transmission system. Network 2 is more highly connected than network 1. Estimating both topologies allows for the possibility that arbitrage opportunities may not fully be exploited over networks with low connectivity.

TABLE 6 ABOUT HERE

The third network is for all of the nodes for which price data are available in the East Texas and the Louisiana Onshore region. This network configuration allows testing between two regions with high connectivity. The fourth network consists of all nodes in the Louisiana Onshore region. This is the most highly connected region (see Figure 7).

The data are split into three equal periods: July 1987 to June 1988, July 1988 to June 1989, and July 1989 to June 1990. The data are segmented in this way so that each period begins and ends in off peak periods. Preliminary estimation showed that lag lengths longer than three were insignificant, so three lags were used for all of the estimated models.[28]

Table 6 shows the likelihood ratio test statistic for the hypothesis that there are no unexploited arbitrage opportunities across the network. For the earlier two time periods, the null hypothesis of a fully arbitraged network can be rejected soundly for each topology. In the last period, July 1989 to June 1990, the null hypothesis cannot be rejected, and the marginal significance levels are very high.[29]

To demonstrate graphically the meaning of these results, price propagation experiments were conducted for network 1.[30] Using the estimated model for each time period, the following experiment was conducted for each node. The price at one node in the network is increased by a one standard deviation

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[28] These vector autoregressions have little structure imposed upon them. For example, with three lags the estimated model for network 3 has over 250 free parameters.

[29] The marginal significance levels for the 1989-1990 time period are quite high. They are 0.95, 1.00, 0.87, and 0.46, respectively. The interpretation is that we are not even close to rejecting the Arbitrage-Free hypothesis.

[30] The results are similar for all other networks. In fact, they are the most dramatic for network 2.

exogenous shock (called the impulse). Then, the response of prices at all nodes was computed for successive time periods.[31]

FIGURES 14,15 AND 16 ABOUT HERE

The intuition behind these impulse-response functions is that if the pressure of arbitrage is strong, then the nonequilibrium relative prices caused by the exogenous price shock at any node will be exploited quickly, and prices will converge rapidly back to the Arbitrage Free equilibrium. Figures 14, 15, and 16 show graphs of the impulse response functions for three estimation periods. Comparison of the 1987-88 impulse response functions with those for 1989-90 illustrates the dramatic change in price convergence. In the earlier periods, arbitrage works more slowly, and prices sometimes take six or seven trading days to converge back to the equilibrium level. For the later period, price shocks at each node are damped out of the national pipeline network daily.

6. Conclusions

Spot prices at various geographic locations became more highly correlated since pipelines became full fledged transportation firms offering contract carriage. Correlations between nodes that are circuitously-connected are nearly as high as

[31] To compute the impulse response functions, the residuals from (2) were orthogonalized using the Choleski factor. Because the Choleski factor is sensitive to the ordering of the equations, the impulse response functions were computed for many alternative orderings. The results were found to be insensitive to the ordering used because the contemporaneous correlations of the residuals across equations were of small magnitude.

correlations between directly-connected nodes. These findings support the hypothesis that the separate natural gas markets have become integrated into one national network of market.

If the price of natural gas were adjusted for transmission cost to a single base node, the competitive "law of one price" would hold across the network. As measured by the variance, the pattern of gas prices across fields is relatively stable. Relative spot prices do change somewhat in the winter; however, the change in variance is of small magnitude and is economically insignificant. Some variation in price spreads is to be expected because transmission costs along certain pipelines vary by season and pipeline capacity constraints will sometimes bind.

The pattern of prices across the network are consistent with an equilibrium that is free of arbitrage opportunities. These results are robust to the particular network configuration chosen. They show that the price of gas at each node in the national transmission network fully reflects the marginal value of gas at the other nodes.

The analysis makes clear that the institutions that market participants created to organize and coordinate the industry are doing just that. Access of gas market participants to pipeline transportation integrated the previously separate markets. The new market is disciplined by arbitrage across the network of interconnecting pipelines. This discipline leads to an equilibrium which is free of arbitrage opportunities and prices lead to allocative efficiency.

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Table 1 - Interconnection Nodes listed by region and pipeline

North Texas

ANR Pipeline Company
Natural Gas Pipeline of America
Northern Natural Gas Company
Panhandle Eastern Pipe Line Company

East Texas

Natural Gas Pipeline of America
Tennessee Gas Pipeline Company
Trunkline Gas Company

Louisiana

Texas Gas Transmission
ANR Pipeline Company
Columbia Gas Transmission
Tennessee Gas Pipeline Company
Trunkline Gas Company
United Gas Pipe Line Company
Southern Natural Gas Company
Natural Gas Pipeline of America

South Texas

Natural Gas Pipeline of America
Tennessee Gas Pipeline Company
Trunkline Gas Company

West Texas

El Paso Natural Gas Company
Transwestern Pipeline Company

Oklahoma

ANR Pipeline Company
Natural Gas Pipeline of America
Northern Natural Gas
Oklahoma Natural Gas
Panhandle Eastern Pipe Line Company

Table 2

Correlation of Price Differences Orthogonal to Seasonal Demand

1984-5

	Appalachia	Louisiana	Oklahoma	Rockies
Louisiana	0.012			
Oklahoma	0.092	0.164		
Rockies	0.063	0.062	0.351	
Texas	0.299	0.548	0.400	0.166

1986-7

	Appalachia	Louisiana	Oklahoma	Rockies
Louisiana	0.506			
Oklahoma	0.477	0.936		
Rockies	0.787	0.671	0.597	
Texas	0.545	0.920	0.916	0.658

1988-9

	Appalachia	Louisiana	Oklahoma	Rockies
Louisiana	0.860			
Oklahoma	0.846	0.976		
Rockies	0.701	0.800	0.781	
Texas	0.793	0.962	0.962	0.801

Z-statistic for change in correlation between 1984-5 and 1988-9

	Appalachia	Louisiana	Oklahoma	Rockies
Louisiana	4.101			
Oklahoma	3.725	6.529		
Rockies	2.580	3.318	2.181	
Texas	2.468	4.342	4.956	2.989

Interregional Price Spreads

Table 3a.

1984-1985

Regions	Mean Spread	Std. Dev.	Minimum	Maximum
Appalachia-Rockies	.446	.220	-.01	.91
Appalachia-Louisiana	.339	.184	-.12	.65
Appalachia-Oklahoma	.495	.185	.16	.85
Appalachia-Texas	.287	.171	-.23	.51
Rockies-Louisiana	-.108	.145	-.44	.11
Rockies-Oklahoma	.049	.136	-.24	.32
Rockies-Texas	-.160	.169	-.56	.13
Louisiana-Oklahoma	.156	.113	.04	.51
Louisiana-Texas	-.052	.105	-.24	.13
Oklahoma-Texas	-.208	.155	-.60	.01

Table 3b.

1988-1989

Regions	Mean Spread	Std. Dev.	Minimum	Maximum
Appalachia-Rockies	.696	.180	.36	.94
Appalachia-Louisiana	.327	.132	-.06	.55
Appalachia-Oklahoma	.418	.128	.05	.62
Appalachia-Texas	.377	.141	-.02	.59
Rockies-Louisiana	-.370	.120	-.67	-.18
Rockies-Oklahoma	-.279	.114	-.54	-.04
Rockies-Texas	-.320	.112	-.56	-.12
Louisiana-Oklahoma	.091	.027	.05	.17
Louisiana-Texas	.050	.042	-.02	.17
Oklahoma-Texas	-.041	.043	-.12	.07

TABLE 4 - PEARSON CORRELATION OF 1988's BIDWEEK PRICES

	WTXelpaso	WTXtransw	ETXngpl	ETXtenn	ETXtrunk	NTXanr	NTXngpl
WTXelpaso	1.0000						
WTXtransw	0.9972	1.0000					
ETXngpl	0.8324	0.8413	1.0000				
ETXtenn	0.8169	0.8283	0.9980	1.0000			
ETXtrunk	0.8460	0.8550	0.9943	0.9942	1.0000		
NTXanr	0.7891	0.7886	0.9018	0.9019	0.9165	1.0000	
NTXngpl	0.8486	0.8510	0.9325	0.9310	0.9459	0.9882	1.0000
NTXnorth	0.8790	0.8813	0.9581	0.9545	0.9663	0.9710	0.9904
NTXpepl	0.8262	0.8293	0.9284	0.9270	0.9407	0.9948	0.9974
STXngpl	0.8123	0.8231	0.9964	0.9941	0.9864	0.8646	0.9007
STXtenn	0.8017	0.8150	0.9949	0.9982	0.9907	0.8799	0.9116
STXtrunk	0.8460	0.8550	0.9943	0.9942	1.0000	0.9165	0.9459
LAanr	0.8169	0.8254	0.9964	0.9962	0.9947	0.9263	0.9487
LAcol	0.8156	0.8262	0.9973	0.9977	0.9962	0.9157	0.9419
LAngpl	0.8191	0.8299	0.9964	0.9958	0.9948	0.8998	0.9294
LAsonat	0.8150	0.8219	0.9811	0.9811	0.9877	0.9618	0.9732
LAtenn	0.8198	0.8309	0.9950	0.9978	0.9945	0.9227	0.9484
LAtexgas	0.8430	0.8521	0.9943	0.9932	0.9977	0.9303	0.9582
LAtrunk	0.8460	0.8550	0.9943	0.9942	1.0000	0.9165	0.9459
LAunited	0.7877	0.7930	0.9775	0.9763	0.9845	0.9285	0.9459
OKanr	0.8180	0.8171	0.9188	0.9156	0.9302	0.9966	0.9931
OKngpl	0.8639	0.8683	0.9309	0.9293	0.9444	0.9786	0.9977
OKnorth	0.8837	0.8860	0.9471	0.9433	0.9597	0.9730	0.9924
OKong	0.8817	0.8866	0.9622	0.9596	0.9701	0.9608	0.9897
OKpepl	0.8151	0.8189	0.9311	0.9311	0.9433	0.9953	0.9959

	NTXnorth	NTXpepl	STXngpl	STXtenn	STXtrunk	LAanr	LAcol
NTXnorth	1.0000						
NTXpepl	0.9863	1.0000					
STXngpl	0.9340	0.8961	1.0000				
STXtenn	0.9393	0.9071	0.9952	1.0000			
STXtrunk	0.9663	0.9407	0.9864	0.9907	1.0000		
LAanr	0.9644	0.9469	0.9879	0.9915	0.9947	1.0000	
LAcol	0.9596	0.9394	0.9913	0.9946	0.9962	0.9990	1.0000
LAngpl	0.9520	0.9260	0.9933	0.9955	0.9948	0.9962	0.9978
LAsonat	0.9777	0.9749	0.9640	0.9720	0.9877	0.9923	0.9894
LAtenn	0.9644	0.9448	0.9869	0.9942	0.9945	0.9979	0.9982
LAtexgas	0.9723	0.9540	0.9841	0.9871	0.9977	0.9970	0.9974
LAtrunk	0.9663	0.9407	0.9864	0.9907	1.0000	0.9947	0.9962
LAunited	0.9482	0.9447	0.9657	0.9697	0.9845	0.9880	0.9870
OKanr	0.9800	0.9974	0.8844	0.8930	0.9302	0.9383	0.9290
OKngpl	0.9916	0.9923	0.8999	0.9101	0.9444	0.9441	0.9382
OKnorth	0.9984	0.9881	0.9210	0.9276	0.9597	0.9553	0.9509
OKong	0.9962	0.9815	0.9398	0.9458	0.9701	0.9682	0.9647
OKpepl	0.9850	0.9995	0.8997	0.9125	0.9433	0.9503	0.9430

	LAngpl	LAsonat	LAtenn	LAtexgas	LAtrunk	LAunited	OKanr
LAngpl	1.0000						
LAsonat	0.9833	1.0000					
LAtenn	0.9953	0.9892	1.0000				
LAtexgas	0.9937	0.9927	0.9958	1.0000			
LAtrunk	0.9948	0.9877	0.9945	0.9977	1.0000		
LAunited	0.9814	0.9893	0.9819	0.9886	0.9845	1.0000	
OKanr	0.9130	0.9686	0.9334	0.9446	0.9302	0.9404	1.0000
OKngpl	0.9263	0.9662	0.9453	0.9561	0.9444	0.9361	0.9856
OKnorth	0.9437	0.9735	0.9558	0.9661	0.9597	0.9431	0.9810
OKong	0.9581	0.9774	0.9701	0.9774	0.9701	0.9538	0.9719
OKpepl	0.9299	0.9778	0.9490	0.9559	0.9433	0.9477	0.9963

	OKngpl	OKnorth	OKong	OKpepl
OKngpl	1.0000			
OKnorth	0.9934	1.0000		
OKong	0.9928	0.9951	1.0000	
OKpepl	0.9898	0.9864	0.9800	1.0000

TABLE 5 - PEARSON CORRELATION OF 1990'S BIDWEEK PRICES

	WTXelpaso	WTXtransw	ETXngpl	ETXtenn	ETXtrunk	NTXanr	NTXngpl
WTXelpaso	1.0000						
WTXtransw	0.9958	1.0000					
ETXngpl	0.9618	0.9657	1.0000				
ETXtenn	0.9237	0.9348	0.9908	1.0000			
ETXtrunk	0.9588	0.9636	0.9988	0.9937	1.0000		
NTXanr	0.9337	0.9434	0.9946	0.9967	0.9948	1.0000	
NTXngpl	0.9827	0.9845	0.9945	0.9760	0.9929	0.9813	1.0000
NTXnorth	0.9949	0.9926	0.9733	0.9376	0.9689	0.9489	0.9894
NTXpepl	0.9572	0.9626	0.9985	0.9929	0.9992	0.9958	0.9920
STXngpl	0.9722	0.9749	0.9987	0.9855	0.9973	0.9905	0.9973
STXtenn	0.9350	0.9452	0.9926	0.9991	0.9960	0.9956	0.9817
STXtrunk	0.9653	0.9693	0.9983	0.9904	0.9993	0.9919	0.9958
LAanr	0.9369	0.9495	0.9919	0.9972	0.9943	0.9963	0.9828
LAcol	0.9240	0.9383	0.9890	0.9982	0.9912	0.9958	0.9758
LAngpl	0.9468	0.9570	0.9954	0.9961	0.9964	0.9956	0.9883
LAsonat	0.9345	0.9469	0.9885	0.9940	0.9910	0.9908	0.9807
LAtenn	0.9295	0.9418	0.9905	0.9978	0.9925	0.9951	0.9789
LAtexgas	0.9107	0.9275	0.9821	0.9959	0.9852	0.9925	0.9671
LAtrunk	0.9533	0.9597	0.9982	0.9959	0.9997	0.9963	0.9904
LAunited	0.9509	0.9578	0.9942	0.9926	0.9963	0.9909	0.9900
OKanr	0.9337	0.9434	0.9946	0.9967	0.9948	1.0000	0.9813
OKngpl	0.9746	0.9758	0.9957	0.9820	0.9952	0.9838	0.9982
OKnorth	0.9939	0.9931	0.9766	0.9440	0.9727	0.9537	0.9921
OKong	0.9844	0.9830	0.9896	0.9679	0.9886	0.9730	0.9962
OKpepl	0.9555	0.9611	0.9983	0.9934	0.9990	0.9962	0.9911

	NTXnorth	NTXpepl	STXngpl	STXtenn	STXtrunk	LAanr	LAcol
NTXnorth	1.0000						
NTXpepl	0.9687	1.0000					
STXngpl	0.9799	0.9969	1.0000				
STXtenn	0.9465	0.9947	0.9889	1.0000			
STXtrunk	0.9748	0.9980	0.9978	0.9940	1.0000		
LAanr	0.9494	0.9943	0.9890	0.9982	0.9928	1.0000	
LAcol	0.9383	0.9912	0.9841	0.9976	0.9884	0.9987	1.0000
LAngpl	0.9581	0.9956	0.9932	0.9978	0.9956	0.9988	0.9974
LAsonat	0.9476	0.9914	0.9851	0.9956	0.9899	0.9975	0.9972
LAtenn	0.9421	0.9924	0.9865	0.9979	0.9901	0.9985	0.9994
LAtexgas	0.9252	0.9855	0.9767	0.9949	0.9819	0.9966	0.9989
LAtrunk	0.9638	0.9990	0.9961	0.9975	0.9983	0.9959	0.9935
LAunited	0.9630	0.9952	0.9918	0.9958	0.9970	0.9955	0.9929
OKanr	0.9489	0.9958	0.9905	0.9956	0.9919	0.9963	0.9958
OKngpl	0.9818	0.9934	0.9970	0.9868	0.9974	0.9855	0.9796
OKnorth	0.9993	0.9723	0.9826	0.9529	0.9788	0.9560	0.9455
OKong	0.9900	0.9865	0.9931	0.9745	0.9922	0.9726	0.9636
OKpepl	0.9671	1.0000	0.9965	0.9949	0.9976	0.9944	0.9915

	LAngpl	LAsonat	LAtenn	LAtexgas	LAtrunk	LAunited	OKanr
LAngpl	1.0000						
LAsonat	0.9972	1.0000					
LAtenn	0.9983	0.9983	1.0000				
LAtexgas	0.9941	0.9957	0.9981	1.0000			
LAtrunk	0.9972	0.9923	0.9944	0.9881	1.0000		
LAunited	0.9972	0.9963	0.9946	0.9890	0.9958	1.0000	
OKanr	0.9956	0.9908	0.9951	0.9925	0.9963	0.9909	1.0000
OKngpl	0.9907	0.9835	0.9829	0.9711	0.9934	0.9926	0.9838
OKnorth	0.9643	0.9551	0.9493	0.9338	0.9679	0.9695	0.9537
OKong	0.9787	0.9673	0.9665	0.9528	0.9855	0.9820	0.9730
OKpepl	0.9954	0.9912	0.9925	0.9859	0.9991	0.9946	0.9962

	OKngpl	OKnorth	OKong	OKpepl
OKngpl	1.0000			
OKnorth	0.9850	1.0000		
OKong	0.9954	0.9912	1.0000	
OKpepl	0.9926	0.9706	0.9856	1.0000

Table 6 - Network "No Arbitrage Opportunities" Test*

Network	Injection Nodes	Regions	1987-88	1988-89	1989-90	$\chi^2_{.05}$
1	El Paso Trunkline Panhandle Tennessee NGPL Northern	West Texas East Texas North Texas South Texas Louisiana Oklahoma	268.40	192.80	84.53	134.35
2	El Paso NGPL NGPL NGPL Tennessee NGPL	West Texas East Texas North Texas South Texas Louisiana Oklahoma	256.05	232.29	11.60	134.35
3	NGPL Tennessee Trunkline ANR Columbia Tennessee Texas Gas Trunkline United	East Texas East Texas East Texas Louisiana Louisiana Louisiana Louisiana Louisiana Louisiana	308.07	297.69	226.85	290.02
4	ANR Columbia Tennessee Texas Gas Trunkline United	Louisiana Louisiana Louisiana Louisiana Louisiana Louisiana	193.08	192.39	110.45	134.35

* χ^2 statistic for H_o: $\gamma_{i,l}=0 \ \forall \ i,l$

Pipeline Application/Approval for Contract Carrier Status

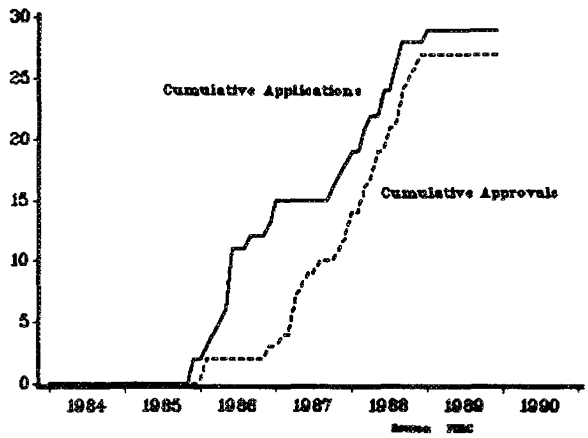


Figure 2.

Transported Volumes by User Category

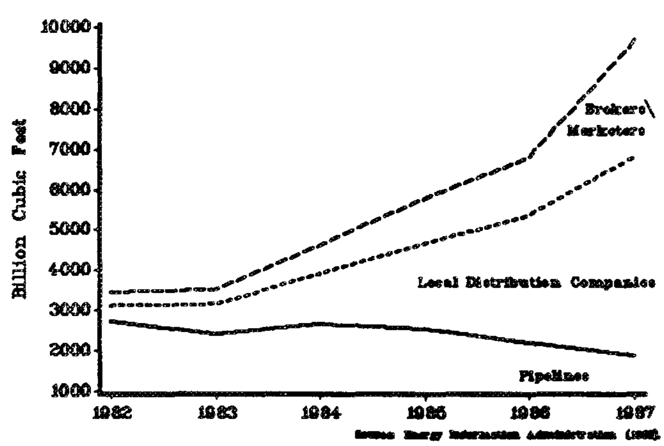


Figure 3.

Number of Nodes for which Daily Spot Prices Reported

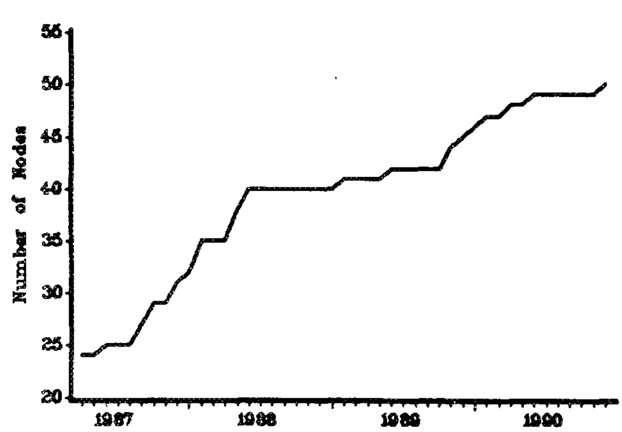


Figure 4.

Figure 9.

Natural Gas Spot Prices by Region

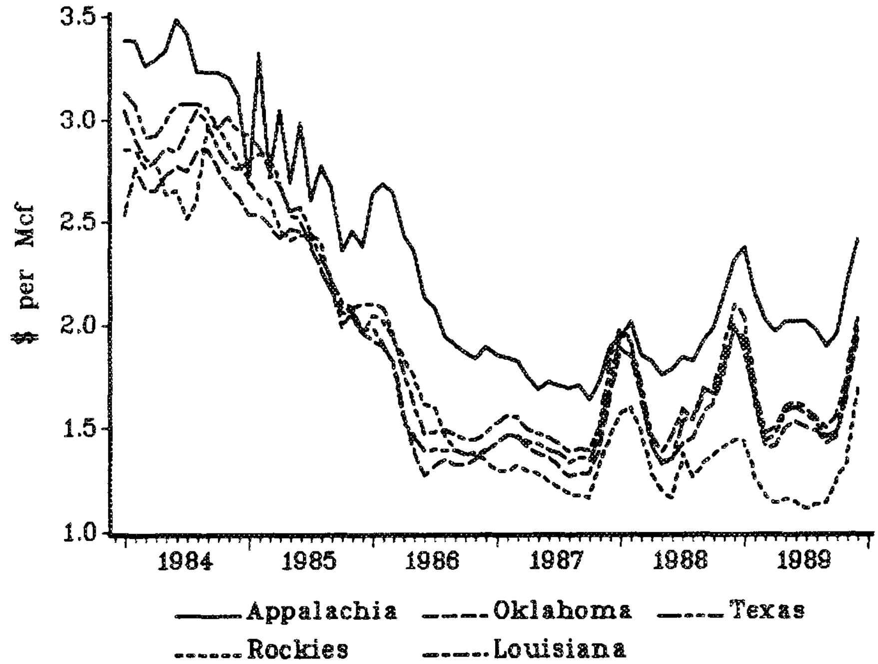
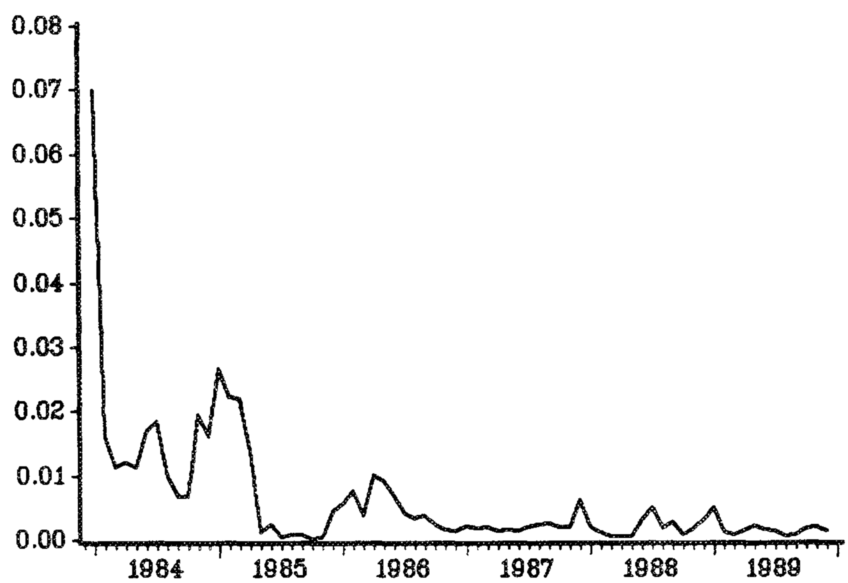


Figure 10.

Variance of Spot Prices across Regions



Regions: Louisiana, Oklahoma, Texas. Source: Author's calculations

Std. Deviation of Bidweek Prices across Nodes

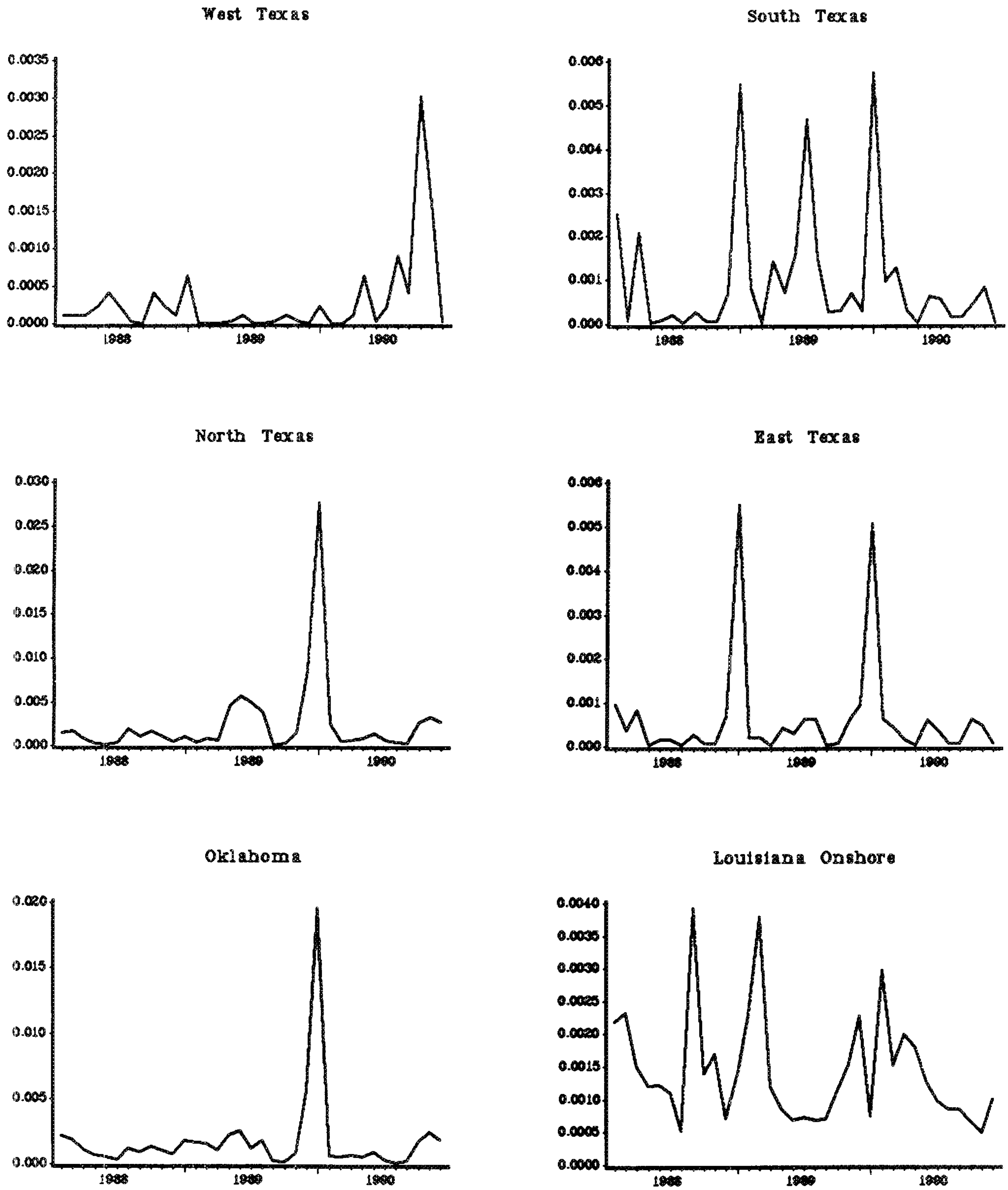


Figure 11.

Figure 12.

Std. Deviation of Daily Spot Prices across Nodes

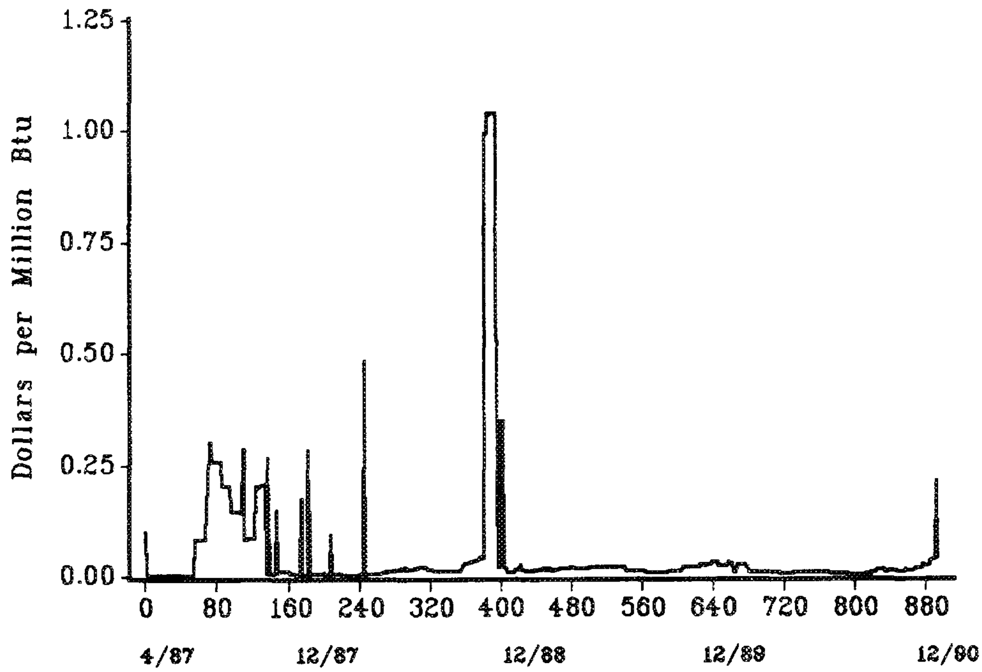
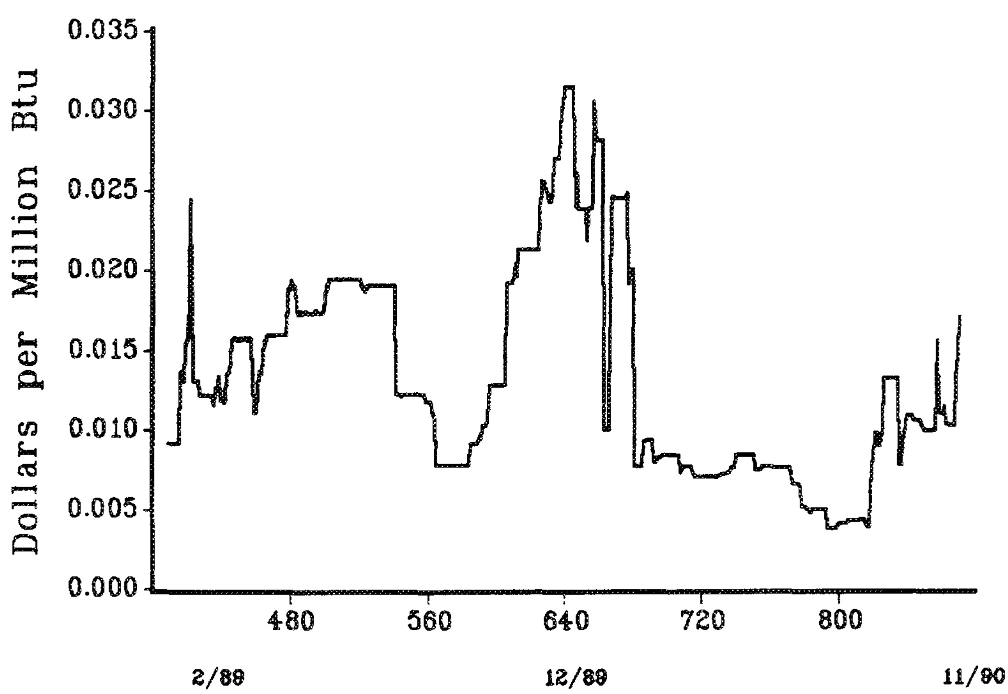


Figure 13.

Std. Deviation of Daily Spot Prices across Nodes



Impulse Response Functions

Estimation Period: July 1987 to June 1988

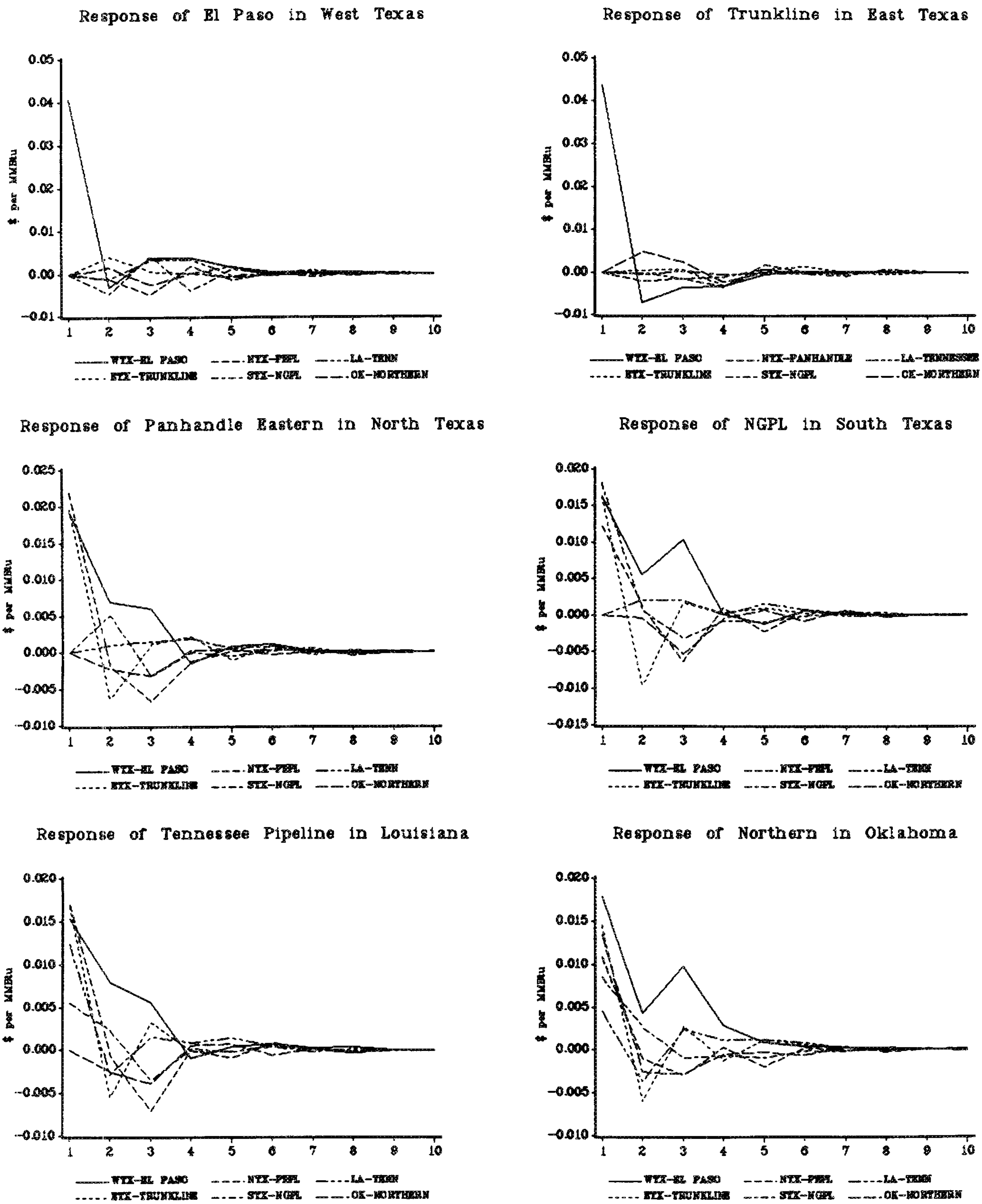


Figure 14

Impulse Response Functions

Estimation Period: July 1988 to June 1989

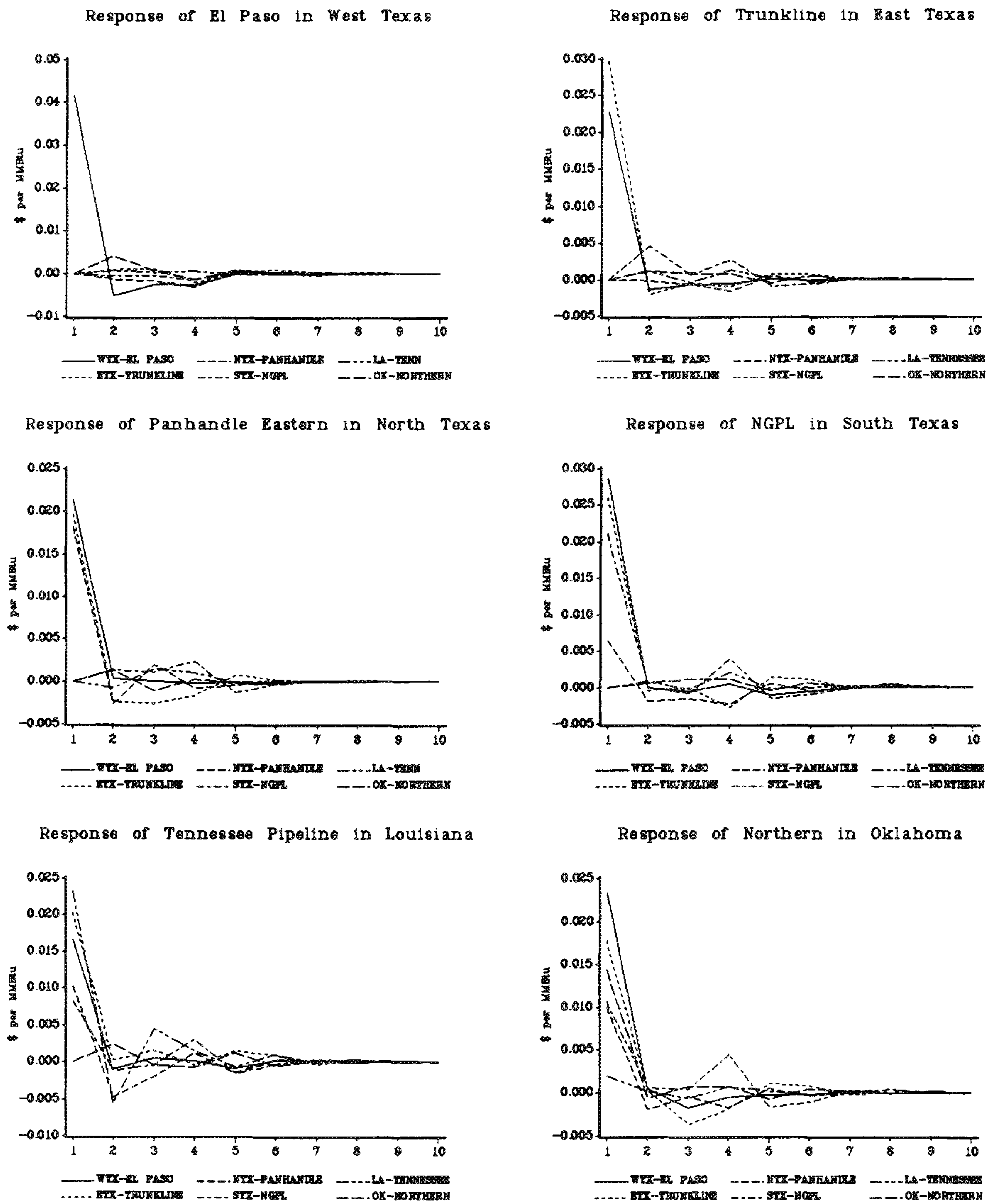


Figure 15

Impulse Response Functions

Estimation Period: July 1989 to June 1990

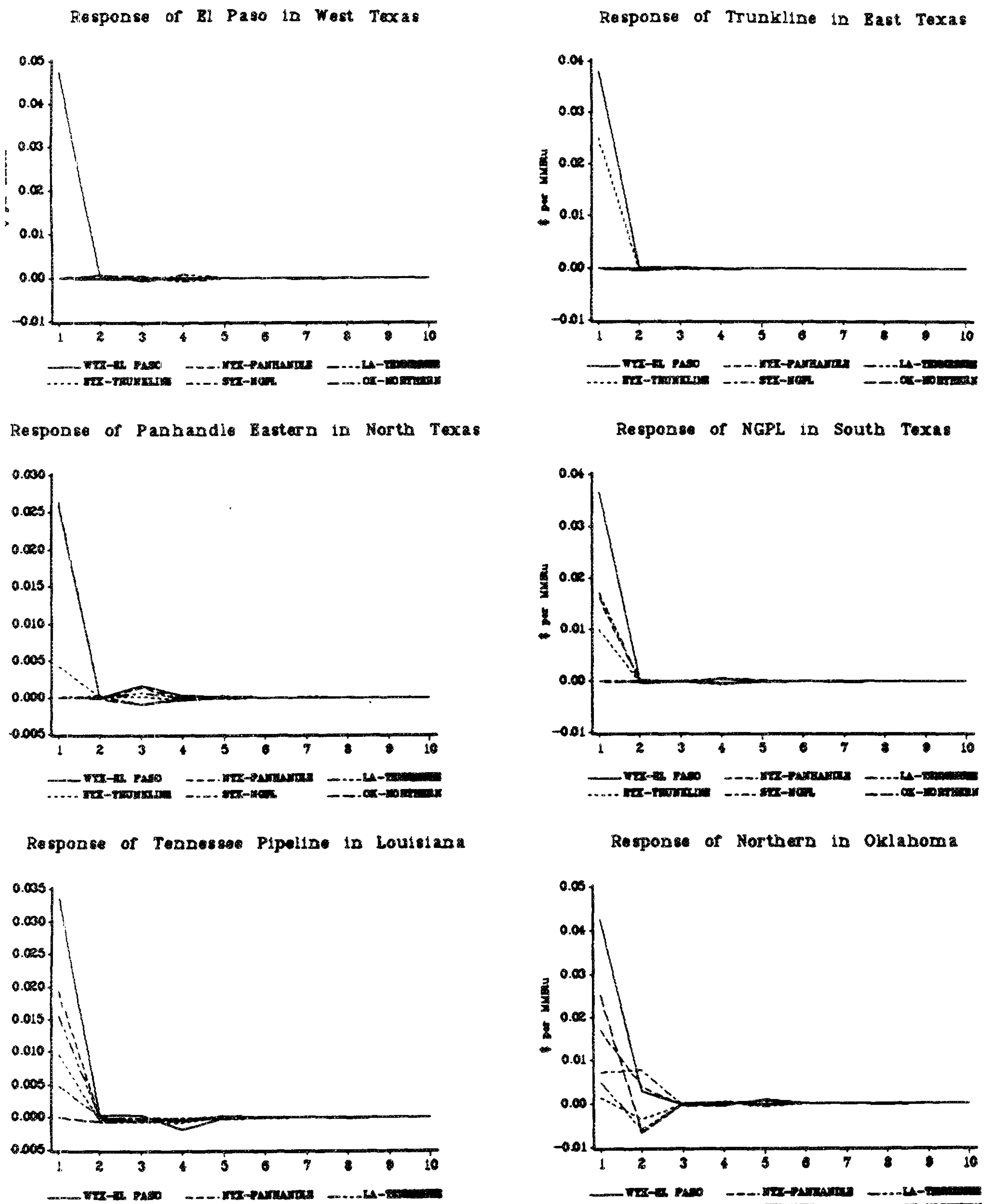


Figure 16