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When Barriers to Markets Fall: Pipeline Deregulation, Spot Markets, and the Topology of the Natural Gas Market

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April 8, 1992

Abstract

Until 1984, Federal regulation sanctioned monopoly as the primary mechanism for distributing natural gas. Pipelines were granted protected markets and permitted to acquire and distribute gas only through long-term contracts. To buy or sell gas, users and producers had to deal with the pipeline, they could not deal directly. Gas markets failed to exist. In 1985, pipelines were given the option to become "open access" pipelines who transported gas. This change dissolved the barriers to markets and, for the first time in more than fifty years, authorized competition. In this paper, we observe and evaluate the emergence, evolution and performance of natural gas spot markets in this new environment. We discover that spot markets flourished in

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the absence of regulatory barriers to their existence; more than fifty spot markets came into existence and quickly replaced long-term contracts and pipelines as sources of gas. The spot price evidence reveals that open access changed the topology of the pipeline network: the balkanized and disconnected network of gas markets created by regulation became more strongly connected and spot prices converged and became more correlated throughout the network. By the end of our sample period, gas markets had become liquid and informationally efficient—demand or supply shocks are strongly damped across the network, and the price at any point contains all the information in the network. The spatially separated spot markets are now so strongly connected that they form a single national market for natural gas.

1 Introduction

Regulatory policies suppressed markets by organizing the natural gas industry along the lines suggested by the theory of natural monopoly: a single pipeline was authorized to link a city market with a producing area; entry was limited; transportation tariffs and gas prices were controlled; customers were unable to deal directly with producers because pipelines were required to be merchant-carriers who owned the gas they transported; gas sales were arranged through long-term contracts.[1] Because of these restrictions, gas markets failed to exist.

Beginning in 1985, Federal regulators allowed natural gas pipelines to offer transportation to their customers.[2] Access to transportation gave gas buyers and sellers access to one another and competition became the fundamental force determining gas prices. Removing the regulatory barrier between gas buyers and sellers brought forth new markets where none had existed before. When a pipeline elected to transport gas, new spot markets opened in the fields connected to it. The number of markets reporting spot prices grew in step with the number of pipelines offering transportation—in the period from 1985 to the present, the number of spot markets grew from a handful to over fifty. There are spot markets in every production field and at many of the points where major pipelines interconnect.

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[1] Scherer includes pipelines as "reasonably clear examples" of natural monopoly (1980, p. 482.)

[2] FERC Order 436, and Order 500.

Authorizing pipelines to transport gas for others also created the means for tying spot markets together. Gas buyers, and brokers acting on their behalf, can combine transportation contracts on separate pipelines to create connected transportation systems that extend over several pipelines and many fields. By 1990, it was possible to make delivery throughout most of the pipeline network and this capability became the basis for a futures market.[3]

Most major natural gas pipelines have shed their merchant carrier status to become contract transporters of gas. By now, more than 80 per cent of the natural gas delivered by pipelines is purchased directly from the field by the customer, or brokers acting on their behalf, and transported by the pipeline.[4] These changes transformed the gas industry and this transformation is the focus of our study.

Our evidence shows that as more pipelines elected to transport gas, new markets opened, the network of pipelines became more strongly connected, and prices converged throughout the network. Over the six year period of our sample of spot prices, one can observe the gas market converging to informational efficiency. In the earliest two-year subsample, the hypothesis of informational efficiency can be rejected; in the second two-year subsample, the hypothesis is weakly accepted (cannot be rejected), and in the third two-year subsample, the hypothesis is strongly accepted (the contrary hypothesis is strongly rejected). Three complementary pieces of evidence indicate that, by 1990, the gas market had become informationally efficient: prices are a martingale with respect to price sequences at all vertices in the network; price spreads between points in the network are a martingale; price changes are a white noise process. Four years after FERC authorized gas markets, competition was enforcing the law of one price.

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[3] The market opened April 1990 at the New York Mercantile Exchange. Thirty day contracts for delivery to a hub in Louisiana up to a year into the future are traded.

[4] Giving pipelines the option to shed their merchant/carrier status and just offer transportation was FERC's attempt to correct regulatory errors; it was not a conscious decision to change the way pipelines are regulated (Teece and Dirrheimer, 1989; Smith, De Vany, and Michaels, 1987).

2 The Institutions

There are three sectors in the natural gas industry: production, transmission and distribution. Natural gas pipelines transport gas between the production and the distribution sectors. Of the three possible forms of transmission service that pipelines could have offered—merchant carriage, contract carriage, or common carriage—regulation forced them to be merchant carriers. As we shall show, this choice restricted competition.

2.1 Merchant Carriage

The natural gas industry was vertically integrated during the 1930's, but, under the Natural Gas Act, Congress re-organized the industry as a system of separate merchant carrier pipelines. Vertical integration was discouraged[5], entry was controlled, and pipeline tariffs and gas prices were regulated. Merchant carrier pipelines were required to own the gas they transported. Pipelines were required to tie the sale of gas to its transportation and 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, but disconnected, network of pipelines. Individual pipelines were constructed as new supplies were found and as the demand for natural gas increased. The Federal Power Commission (FPC) certificated construction of a new pipeline only after it had shown that it had reserves to supply its downstream customers for a period of 15 to 20 years. To achieve this end, pipelines entered long-term contracts with producers under which the reserves in the gas wells were dedicated to the pipeline. Pipelines could not be abandoned, and contracts could not be renegotiated without the approval of the FPC.

This regulatory process balkanized gas markets. It created a disconnected network topology which prevented gas from flowing from any field to any

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[5] Mulherin (1986) shows that the Federal Power Commission created a disincentive for pipelines to integrate vertically into the production fields.

city. The cities and producing fields connected by pipelines were isolated from the fields and cities connected by other pipelines. Pipelines operated independently of one another, each supplying its own cities with its dedicated gas supplies. The disconnected network topology and limitations on trading prevented markets from existing.[6]

2.2 Deregulation and Open Access

Despite regulation that attempted to maintain high levels of reliability to users, federal price controls caused shortages of natural gas in the 1960's and 1970's.[7]. In response to these shortages, Congress passed the Natural Gas Policy Act in 1978. The Act deregulated the field price of gas in steps and completely deregulated the price of some types of gas. In 1979, there was a major interruption of world oil supplies. Reeling from gas curtailments, a run-up in oil prices, and uncertainty over the deregulation of field prices, many pipelines signed long-term contracts to buy large volumes of gas. When gas prices fell after wellhead prices were deregulated, these pipelines faced infeasible minimum purchase obligations of high-priced gas. Many of them renegotiated their contracts with producers. In exchange for partial release from their purchase obligations, these pipelines offered to transport gas for producers, or their customers—this was the beginning of transportation and competition in gas markets.

The FERC approved these transportation transactions individually until October 1985 when it issued Order 436 permitting interstate pipelines to transport gas for others under "blanket certificates." This Order formally distinguished and separated the pipeline merchant and transportation functions.[8] After some initial skepticism, pipelines began to make application to become "Open Access" pipelines. As Figure 1 shows, the number of pipeline applications and approvals for Open Access grew rapidly from 1985

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[6] Under the Civil Aeronautics Board, route authorizations were similarly disconnected. The efficiency of the airline hub and spoke system could not be realized fully until deregulation granted the airlines the flexibility to realign their routes (see De Vany, 1972). Pipeline hub and spoke networks are forming through pipeline mergers (EIA, 1986). Brokers are able to create hub and spoke subnetworks without merging pipelines by combining transportation rights on interconnected pipelines.

[7] See, MacAvoy and Pindyck (1975)

[8] Earlier Orders had already dismantled long-term contracts and left pipelines with few options to open access.

to 1990. Within three years of Order 436, nearly all the major pipelines had become open access pipelines.[9]

Open access pipelines offer their traditional service of bundled gas and transportation, although most of their throughput is gas transported for customers. Between 1982 and 1987, transmission of pipeline-owned gas decreased 60%, while transmission of customer-owned gas increased by 180% (EIA, 1989). Transportation accounted for two-thirds of all interstate gas movements by 1987, and in 1991 over 85% of gas shipped in interstate commerce was owned by customers (FERC MegaNOPR, 1991). The rapid shift in the composition of the pipeline's traditional business of selling gas to transporting it for others can be seen in Figure 2, which shows the amount of gas transported for brokers and local distribution companies from 1982 through 1987.

As open access spread through the pipeline network, spot markets opened at fields and interconnection points. The number of spot markets reporting prices to the *Gas Daily* grew from zero in 1985 to around 50 by 1990. The growth in spot markets is evidenced in Figure 3, where it is apparent that the number of markets doubled from 1987 to 1990.

2.3 Contract Carriage

Under merchant carriage, users contracted with pipelines for a firm (uninterruptible) supply of gas up to some maximum daily volume, the "callable" volume. The unused portion of the callable volume was sold as interruptible gas. This gas was subject to interruption; the holder of a firm supply contract had priority over others. In making the transition from merchant to contract carriage, the FERC required the pipeline to permit customers who held firm purchase agreements to convert the callable volume to uninterruptible transmission rights. On making that election, the holder of transmission capacity is obligated to pay a reservation charge which depends only on the volume of gas for which uninterruptible transportation is reserved, and a volumetric charge for each unit of gas shipped. Most of the transmission capacity in the pipeline grid is under contract to the companies who distribute it in the city-gate market to wholesale and retail customers. These local distribution

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[9] Order 436 was vacated by the court; its intent was then carried out through Order 500.

companies (LDCs) were the major buyers of gas before open access and they inherited transportation capacity when their gas contracts were converted to transportation contracts.

Holders of firm transportation contracts may trade with one another or transfer their rights to brokers and other parties. However, FERC has not permitted transportation to become a fully transferable property right.[10] Unused firm transmission capacity reverts to the pipeline which sells it as interruptible transportation. Pipelines monitor throughput and post unused capacity for sale on electronic bulletin boards. These bulletin boards are accessible to all market participants who can buy interruptible transportation at the tariff posted by the pipeline. Because the tariffs may be discounted below the regulated tariff, the price of transportation adjusts continuously to clear the market, up to the maximum regulated tariff. In peak periods, the regulated tariff may become a binding upper limit on the market price of transportation.[11]

As a result of these changes the transportation capacity has been reallocated from pipelines to their customers. There are 21 major interstate pipelines and 1400 local distributors who hold transportation contracts on those lines (Bradley, 1991). If they hold or acquire transportation contracts, 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 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 reduce price disparities anywhere in the network of interconnected pipelines.

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[10] See, Smith, De Vany and Michaels (1987).

[11] Because the pipeline's tariff and its price of gas are regulated and not responsive to demands or capacity constraints, the market price of gas delivered at the maximum tariff may exceed the regulated system gas price of the pipeline in the peak winter heating period. The pipeline's system gas is adversely selected when it is less than the market price.

2.4 Coordinating Gas and Transportation

A transaction for gas specifies a volume with an injection point and a withdrawal point. Metering verifies the volume injected and withdrawn at these points; the molecules are not traced from one location to another. The nature of a transportation contract then is to specify injection and withdrawal points and maximum volumes. This means that traders can "clear" transactions on injection and withdrawal points when they are against the flow direction of the pipeline, or even if there is no interconnection between the points. To illustrate this, suppose pipeline One connects field A and city B and pipeline Two connects field B and city D. To buy an amount of gas from field A for "delivery" to city D on pipeline Two, buy injection for that volume at A and withdrawal at D and sell withdrawal at B and injection at C. At the same time, buy gas at the injection points and sell it at the withdrawal points. For trading to be this sophisticated, traders must be large enough to internally clear these transactions, or some kind of clearing house is needed. Alternatively, the pipelines could be interconnected by adding links in the grid.

All three of the things needed to support gas trading have been done:

1. Brokers capable of transacting throughout the network have come into existence.
2. Mergers and interconnects have been made throughout the network.
3. Market institutions were created to coordinate gas and transportation trades.

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

Pipeline mergers have created extended networks. The technology for interconnecting pipelines quickly developed after 1985, so that it is now possible to interconnect lines with different pressures and to change the flow between them.[12]

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 plan to ship during the following month. These nominations specify the injection point, the withdrawal point, and the volume of gas to be shipped. Customers may nominate volumes only up to the amount of their firm transmission rights. Those pipeline customers who transfer their transmission capacity to third parties are responsible for nominating and paying for it.

During the bidweek, gas users who hold capacity rights purchase the volumes which they nominate for transmission during the following month.[13] 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."

3 Trading and Arbitrage in a Network

With the institutions now in place, we are prepared to model the behavior of prices in pipeline networks. The central issue to be investigated is how the change from merchant carriage to transportation altered prices. We show that, under the regulated system of merchant carriage, only the price *spreads* between fields and cities are determined; the *levels* of these prices are indeterminate. We show that competition makes prices determinant. Then, we model arbitrage in the network and find a relationship between the connectivity of the network and the dispersion of prices. We close the section by modelling informationally efficient prices in a network.

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[12] See *Oil and Gas Journal*, August 6, 1990, pp. 41-48.

[13] The simultaneity of both markets during bid week solves the coordination problem found in experiments. See Section 7 below.

3.1 Trading in a Simple Pipeline Network

Consider the simple system shown in Figure 4 where point 1 is a field where gas is produced (a source) and points 2 and 3 are cities where gas is consumed (sinks). Under the regulated system of merchant-carriage gas could be transported from 1 to 2 and from 1 to 3, but not from 2 to 3—the pipeline was the sole buyer of gas at 1 and the sole seller at points 2 and 3. Entry was closed. If the pipeline rationally attempted to exploit this legally granted monopoly, it would do so by increasing the price spreads $p_2 - p_1$ and $p_3 - p_1$, driving the field price down and the end market prices up. Cost-based rate making controlled only the spread between field and city prices, allowing the pipeline to charge a city price that exceeded the field price by the cost of transmission (determined by regulating the rate of return on the allowed rate base).

To illustrate this point, let c be the (constant) marginal cost of producing gas, and let the regulated tariff between points i and j be ρ_{ij}. Let the upper bound on the value of gas in markets 2 and 3 be v_2, v_3. Then, merchant carriage sets the following constraints on prices:

$$\begin{aligned} p_1 &\geq c \\ p_2 &\geq p_1 + \rho_{12} \\ p_2 &\leq v_2 \\ p_3 &\geq p_1 + \rho_{13} \\ p_3 &\leq v_3 \end{aligned}$$

Prices are bounded between production cost and the maximum values consumers will pay. Even informed regulation that sets price spreads equal to transmission cost does not narrow the bounds on prices, they could be at the upper or lower limits (only the spreads are determined). This method of regulation determines the spread between city prices and the field price, but leaves their level indeterminate—whatever the pipeline pays for gas is passed through as a cost to customers.[14]

The transition to contract carriage changed this. Under contract carriage, buyers and sellers meet in an auction for gas and establish a market price in

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[14] The incentive problem which this pass through of gas cost creates is one reason the FERC conducts prudence reviews of pipeline gas purchases.

the field. City prices will equal this price plus the regulated cost of transmission. Since the number of buyers and sellers on a pipeline is typically very large, the field price will tend to go to the competitive level. Even if there are only a few suppliers, the auction institution and the inability of suppliers to withhold supply indefinitely will move price toward the competitive level, which we take to be a field price near c.

Contract carriage permits buyers at 3 to buy from sellers at 2, which connects the system to form the triangle in the right hand side of Figure 4. The possibility of triangle arbitrage adds the following constraints on prices:

$$\begin{aligned} p_3 &\leq p_2 + \rho_{23} \\ p_3 &\leq p_1 + \rho_{13} \\ p_2 &\leq p_3 + \rho_{32} \end{aligned}$$

Because it is possible to ship from 1 to 3 and 2 to 3 when transportation is open, two new constraints are placed on the price at 3. In addition, because of the possibility of "backhaul" from 3 to 2, triangle arbitrage adds another constraint on the price at 2.

The importance of the additional constraints imposed on prices by open transportation may be seen by solving both the closed and open transportation systems for prices. If we assume that prices are maximized subject to the constraints and let the tariffs be $\rho_{12} = 1, \rho_{13} = 2, \rho_{23} = 1.5$, then, under the merchant system, prices are $p_1 = 23, p_2 = 25, p_3 = 25$. Under the contract transportation system, prices are $p_1 = 22.5, p_2 = 23.5, p_3 = 25$. Even though no new capacity has been added to the system, prices decline; they decline because triangle arbitrage is made possible by opening the link between 2 and 3 to trade.

In addition to the effect of triangle arbitrage, competition in the field (arbitrage by buyers over suppliers) will drive p_1 toward the competitive level, taking p_2 and p_3 with it. If c is 10, then the overall effect of opening the system to competition would drive prices to: $p_1 = 10, p_2 = 11, p_3 = 12.5$.[15]

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[15] The evidence suggests that something like this was the result of open access; field prices declined dramatically and city gate prices followed. But, burner tip prices for core consumers have not followed the decline of field and city gate prices.

3.2 Price Convergence and Network Connectivity

It is natural to think that prices will converge as the triangle network in Figure 4 is embedded in a larger one. Contract carriage allows other pipelines to be linked into the system to form a larger, more connected network. Consider the network represented as the directional graph $\mathcal{N}$ in Figure 5. The production fields, pipeline hubs, and the city markets are elements of the set of vertices V of $\mathcal{N}$ and the arcs of the pipeline network are the ordered pairs of the elements of V. The arrows in the figure show the direction of the flow on the arcs. The pipeline network is the ordered pairs of sets of vertices and arcs (V, A). If there is a directed arc (path) from i to j, then j is said to be adjacent to i and the i, j entry of the adjacency matrix $A(\mathcal{N})$ of $\mathcal{N}$ is 1. If there is no arc from i to j, the entry of $A(\mathcal{N})$ is zero. The transitive closure of network $\mathcal{C}(\mathcal{N})$ is shown in Figure 6; it represents the maximally connected network preserving flow direction which contains the vertices of $\mathcal{N}$. $\mathcal{C}(\mathcal{N})$ is obtained if open access permits any trader to inject gas at any source and withdraw gas at any sink in the network (at interconnects, traders do both).

Proposition 1 *Prices converge as the network becomes more connected.*

PROOF To prove this, we need to relate the connectivity of the network to the number of competitors who can contest the market at each vertex and then use a limit argument that shows that prices converge as the network becomes strongly connected.

The number of paths of distance $1, 2, \ldots, \mathcal{D} \leq n - 1$ in the network $\mathcal{N}$ connecting vertices i, j is given by the i, j-th entry in the $n \times n$ matrix $A^{\mathcal{D}}(\mathcal{N})$. As the number of arcs (connections between vertices, or markets) increases, the number of vertices connected by at least one path of length $\leq \mathcal{D}$ increases faster than the square of the number of arcs. This follows because the row sum of $A^{\mathcal{D}}(\mathcal{N})$, which shows all the paths to vertex i from every other vertex, increases by a power of the number of arcs. In a strongly connected network, every entry of $A^{\mathcal{D}}(\mathcal{N})$ is non-zero.

Consider the price set of the network $\mathcal{N}$ with vertex and arc sets (V, A). Let $\mathcal{P}(V, A)$ be the set of vertex prices that are not blocked. If a price set with A arcs is blocked, then the price set with $A + 1$ arcs is blocked and $\mathcal{P}(V, A + 1) \subseteq \mathcal{P}(V, A)$. The price set shrinks as the number of arcs grows because the number of competitors becomes large and the minimum distance between pairs of vertices shrinks.

Proposition 2 *The condition number of $A^{n-1}(\mathcal{N})$ increases as its n vertices are connected by more arcs.*

This proposition follows as a corollary of the preceding proposition. It gives a simple, though not unique, measure of connectivity of a network which we use in our empirical section.

The next result extends the well-known fact that informationally efficient prices are a martingale to a network.

Proposition 3 *Network arbitrage pricing is informationally efficient.*

PROOF Adopting Samuelson's recursive argument (Samuelson, 1965), consider prices at vertex i. Let the futures price quoted in period t for the spot price that will hold T periods from now be $p(T,t)$. Then one period later the quote will be $p(T-1,t+1)$ and we have the sequence

$$p(T,t), p(T-1,t+1), \ldots, p(T-n,t+n), \ldots, p(1,T-1) \tag{1}$$

Arbitrage pricing means that

$$p(T,t) = E[p_{t+T}|\theta_t]$$

for all $T = 1, 2, \ldots$. The information sets associated with (1) are

$$\theta_t, \theta_{t+1}, \ldots, \theta_{t+n}, \ldots, \theta_{t+T-1}$$

and they form a monotone increasing sequence. Thus, (1) can be shown to be a martingale by direct verification:

$$\begin{aligned} E[p(T-1,t+1)|\theta_t] &= E[E[p_{t+T}|\theta_{t+1}]|\theta_t] \\ &= E[p_{t+T}|\theta_t] \\ &= p(T,t) \end{aligned}$$

Equation (1) also holds for the sequence of spot prices beginning $T-1$ periods in the past and ending at T, so spot prices are a martingale.

Now, consider arbitrage over vertices. No arbitrage opportunities over vertices i and j means

$$p(t,j) + \rho_{ij}(t) = E[p(t+1,i)|\theta_{i,t}]$$

so the sequence of spot prices at j is a martingale if the sequence at i is a martingale and $\rho_{ij}(t)$ is either a constant or a constant plus an uncorrelated noise process with zero mean.

If network pricing is a martingale, then the price sequences at each vertex $P_1, P_2, \ldots, P_n$ are martingales with respect to the information sets $I_1, I_2, \ldots, I_n$. On the assumption that transportation tariffs are constants, each price sequence is also a martingale with respect to the information set at any other vertex, so if P_i is a martingale with respect to I_i, then it is a martingale with respect to I_j, $\forall j \in V$.

To model this process over the network, let $i \in N$ index the vertices in the network. The price at vertex i at time t is denoted $p_{i,t}$. Let ϵ_t be a white noise process that may be contemporaneously correlated across vertices, and let W_t represent an exogenous factor that affects the prices at each vertex, such as the weather. Let $l \in [1, L]$ denote the temporal lag of a variable. Then the hypothesis that prices contain no arbitrage opportunities can be tested by estimating the following system of equations.

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

If $\gamma_{j,i,l} \neq 0$, then the past price change at vertex i at time l predicts the current price change at vertex j. A trader could exploit this predictability by buying gas at one vertex and selling it at the other. In the formulation above, the test for arbitrage opportunities is across $N \times N$ interconnections for each of L lags. Testing the arbitrage pricing hypothesis is equivalent to testing the joint hypothesis that all the elements of the $N \times (N \times L + 1)$ matrix Γ corresponding to Equation 2 are equal to zero.

4 The Data

4.1 The Regional Sample

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. Aggregating these disparate price series increases the noise in the data and biases the results away 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.

4.2 The Network Sample

Gas Daily reports both bidweek and daily spot prices of natural gas at over fifty pipeline interconnection vertices within the transmission network. The interconnection vertices 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. We selected twenty-five vertices for which *Gas Daily* has continuously reported *bidweek* spot prices since February 1988. We selected twenty vertices for which *Gas Daily* has continuously reported *daily* spot prices since July 1987. For both samples, the vertices 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 vertices by the region in which they are located and the pipeline to which they are attached.

Bidweek prices are the weighted average price of gas purchased based on volumes and prices for spot deals struck during bidweek. The daily spot prices are a weighted average of each day's trades. These prices are for gas injected into the pipeline at the vertex for which the price is listed. The prices include all gathering and transportation fees incurred to get the gas to the points for which prices are reported. All prices are based on dry packages of five million cubic feet per day (CFD) stated in dollars per million Btu (\$/MMBtu) for spot contracts of 30 days or less.

5 Empirical Results

To see the overall pattern of our results, consider the time series plot of the regional spot prices in Figure 7 demonstrates clearly a pattern of prices that changed over time. The data follow three distinct patterns over three successive time periods: 1984-85 when 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. During the following winter, the price rose in Appalachia while it fell in the Rockies. Even the prices in Louisiana and Texas, the two regions served by the most dense grid of pipelines, do not move together during 1984.

By the end of 1986, about a year into open access transportation, the gas prices begin to move closely together, with each series declining at about the same rate. Since 1987, spot prices in all regions move together.

5.1 Correlations of Regional Spot Prices

To quantify the relation of price movements in different regions to one another, we calculated the Pearson correlation coefficient 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, the first differences of the price series were actually for the correlation analyses. The prices were made orthogonal to a seasonal demand variable before the correlation coefficients are calculated.

To test whether the correlation between regions changed over the sample period, we used Fisher's r to Z transformation.[16] The hypothesis that the

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[16] Let r_{xy} be the sample correlation between x and y and let ρ_{xy} be the population correlation between x and y. Then $Z = 1/2\log((1+r_{xy})/(1-r_{xy}))$ is approximately normally distributed with expectation $E[Z] = 1/2\log((1+\rho_{xy})/(1-\rho_{xy}))$ and variance

correlation is 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 $s_{12} = (1/(n_1 - 3) + 1/(n_2 - 3))^{1/2}$. This test statistic follows a standard normal distribution.

In Table 2 we report the correlations between pairs of vertices for three subsample periods: 1984-85, 1986-87 and 1988-89. The table also gives the value of the test statistic for the hypothesis that there was no change in price correlations between the first and last period. The correlation between prices increased significantly for each region-pair. These results support the hypothesis that these five regions functioned as distinct markets in 1984-85, but evolved over time into one large market.

5.2 Convergence of Price Spreads

If the five separate markets did converge to a single market, then price spreads should have become less volatile. Tables 3a and 3b show the spreads 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. The range and variance of price spreads between Louisiana, Oklahoma, and Texas decreased markedly, and this is shown graphically in Figure 8.

5.3 Correlations of Bidweek Spot Prices

The correlations between the region pairs are high, but there are some patterns to be noted from Table 4. In 1988, prices are more highly correlated between vertices in the same region than between vertices 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 vertices in other regions. 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 even the lowest correlation between prices is 0.97, between the

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$Var[Z] = ((1/(n-3))^{1/2}$ where n is the number of observations used to compute the correlation coefficient (Hays, 1973).

ANR and 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 1988 prices at nearby vertices were more highly correlated than prices at more distant vertices.

In contrast with 1988, the price correlations for 1990 shown in Table 4 are high both between vertices in the same region and between vertices in other regions. The increase in price correlations from 1988 to 1990 is particularly noticeable between those vertices on pipelines in West Texas with vertices on pipelines in other regions. The correlation between ANR in North Texas and El Paso in West Texas is now 0.93. The correlation between vertices located in South Texas and Oklahoma is much higher, about 0.98. The differences of the correlations of 1990 from those of 1988 are two-fold: the correlations are all higher, and the correlations between prices at distant vertices approaches the correlation between prices at more distant vertices.

One way to compute the increase in correlation between more distant vertices in the later time period is to compute the condition number for each correlation matrix. The condition number is the ratio of the largest characteristic value of the matrix to the smallest. It measures the degree of collinearity of the columns in the correlation matrix (Belsley, et. al., 1980), with a high condition number indicating high collinearity. The condition numbers for 1988, 1989, and 1990 are $7.03 \times 10^{16}, 1.43 \times 10^{18}$, and 2.28×10^{22}, respectively. The increasing condition numbers indicate that the correlations are becoming more equal between all pairs of vertices. We showed in Proposition 2 that the condition number of the network is an indication of how strongly connected it is and how many paths there are between vertices. Thus, the interpretation to be placed on the increasing condition numbers of the correlation matrices is that the network has become more connected.

5.4 Convergence of Bidweek Spot Prices

As another measure of price convergence, we computed the maximum spread of prices in the network by taking the highest and lowest prices throughout the network at each point in time. Figure 9 shows the maximum spread of bidweek prices in the network for the 1988-1990 period. Generally the price spread between regions is between 2 cents and 90 cents. The means and standard deviations of spreads are shown in Tables 3a. and 3b. The mean and maximum spreads for the Appalachia-Rockies regions both increased slightly, while all other spreads narrowed. For all regions, the standard deviations of the price spreads decline from 1984-85 to 1988-89. The spreads increase in the winter months because pipelines become congested and do not discount their tariffs during the winter.

6 Testing the Arbitrage Pricing Hypothesis

The daily spot price data were 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 series of price changes are nonstationary was rejected. These tests mean that the price series are not integrated of an order greater than one.

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

Network 3 contains all of the nine vertices for which price data are available in the East Texas and the Louisiana Onshore region. This network covers the largest region and contains the largest number of vertices of any of the networks for which the test is conducted. Network 4 consists of all the vertices in the Louisiana Onshore region; this is the most strongly connected network.

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.

Table 6 shows the likelihood ratio test statistic for the network arbitrage pricing hypothesis. For the earlier two time periods, the null hypothesis of a fully arbitraged network can be rejected soundly for each of the four network topologies. In the last period, July 1989 to June 1990, the null hypothesis cannot be rejected for Networks 1, 2, and 4, and the marginal significance levels are very high. For these networks, the contrary hypothesis is strongly rejected. The arbitrage pricing hypothesis can be rejected for Network 3 in all three sample periods. The significance level declines over time, but the strong arbitrage pricing hypothesis is rejected. In this network, there are $9^2 \times 3 + 9$ unique directions in which arbitrage opportunities must be fully exploited for the strong arbitrage pricing hypothesis to be accepted. For such a large network, this is a very strong condition. The weaker arbitrage pricing hypothesis that the block of the correlation matrix containing Network 3's vertices is nearly singular is accepted.

To demonstrate graphically the meaning of these results, price propagation experiments were conducted for Network 1. Using the estimated model for each time period, the following experiment was conducted for each vertex. The price at one vertex in the network is increased by a one standard deviation exogenous shock (called the impulse). Then, the response of prices at all vertices was computed for successive time periods.

When the force of arbitrage is strong, nonequilibrium relative prices will be exploited quickly, and prices will converge rapidly to the arbitrage pricing equilibrium. Figures 10, 11, and 12 show the impulse response functions on Network 1 for the early, middle and most recent time periods. Comparing these impulse response functions illustrates the dramatic change that has taken place in the speed and range of price convergence. In the 1987-1988 period, arbitrage works, but it may take six or seven trading days for prices to converge to equilibrium. In the middle period, 1987-1989, arbitrage is sufficient to damp price more rapidly and the volatility of the response to the shock is reduced. By 1989-1990, price shocks at each vertex are absorbed in the network within a day or two.

It is worth emphasizing that price shocks are dampened at the vertex where they occur and at every other vertex in the connected three state region for which we have enough data to do the calculations. Prices in a Louisiana production field on the Tennessee Pipeline respond to a price shock in a field in north Texas on the Panhandle Pipeline about as rapidly as they do to a shock in the Louisiana field.

7 Conclusions

7.1 Coordination

Experimental research suggests that there is a potential for coordination failures in the commodity and transportation markets. McCabe, Rassenti and Smith, and Plott found coordination failures in experimental markets in which the gas commodity is purchased separately from transportation. Such a coordination failure would occur when the buyer of gas is unable to arrange for its transportation; in this instance the buyer either has to pay a premium for the transportation or unload the commodity on short notice.

Coordination failures result in short term illiquidity in gas or transportation. Evidence of such failures would be episodes of price volatility and unused transportation (the gas can always be left in the ground). If traders are unloading commitments because of a failure to coordinate gas with transportation, this would be revealed in the prices of transactions made after the bid week auctions closed.

The question then, is have gas market institutions been designed to avoid coordination failures? The evidence suggests that the commodity and transportation markets have successfully been coordinated through three mechanisms. The bid week auction for the commodity is coordinated with advance nominations which shippers make for transportation. Shippers simultaneously are able to buy the commodity and arrange for transportation. In addition, those who hold firm transportation contracts have guaranteed transportation up to the limit of the contract and, hence, are able buy the spot commodity with assurance that they can ship any amount up to their limit. Brokers who buy the commodity to ship via interruptible transportation can make and unmake deals on the commodity throughout bid week as they observe the amount of firm transportation nominated by those who hold it. They have real time information on the amount of capacity booked which they use to make their commodity commitments.

Beyond this institutional evidence is the price evidence. Spot price volatility has narrowed geographically and temporally. Further evidence of successful coordination is that virtually all the transactions for spot gas made after bid week closes are made at the bid week price. That would not be the case if that gas were being sold by a buyer unable to ship it or someone buying gas to cover transportation already acquired. There is no evidence that commodity or transportation “corners” create extreme spot prices.

7.2 Where are New Pipelines Needed?

There is some evidence that lines in the grid become congested from time to time. The spot price spreads between different locations widen seasonally. The only persistently wide spread is between the Rockies and the rest of the supply fields. This gas is far from markets, which lowers the field price to match the delivered prices from other fields to each market. It is not well connected to the national grid and proposals to add pipelines to connect these fields to new markets are before FERC for approval. The spot price evidence correctly identified this market as needing additional transportation. The price spreads also provide a tool for valuing new pipeline projects.

7.3 Monopoly

There is no evidence of bottleneck monopolies in the price data. Prices are highly correlated over all the vertices, near and far, and there is no evidence that prices at vertices served by only one or two pipelines are less correlated than prices at vertices served by three or more pipelines. Price spreads narrowed over time through the network. This suggests that there were non-equilibrium price disparities early on as open transportation began to spread through the network. These early spreads were characteristic of the old system. Markets were separate and not linked to the network. Merchant carriage, dedicated gas, closed entry and a disconnected network prevented other suppliers from contesting markets. Regulation may have created market power which rate regulation alone could not eliminate.

The price spreads in the beginning of open access transportation reflected the way pipeline tariffs were set under regulation. Regulated pipeline tariffs were based on historical cost, so they could differ among pipelines serving the same market for reasons unrelated to the value of transportation or gas in that market. Two pipelines delivering gas to the same city might have different delivered prices simply because their regulated tariffs differed. Competition made them bring their tariffs into line so that they could both deliver into the market at the going price. FERC granted permission for pipelines to discount tariffs in its early transportation programs and this carried over to open access. Pipelines now discount tariffs aggressively to meet the competition.

It would be surprising if one were to find hard evidence of monopoly. This is because the capacity of pipelines is now in the hands of its shippers (there are about 1400 of them). No longer does a single agent hold all of the transportation capacity on a link of the network. The firm capacity on most links is in the hands of the LDCs, who buy and ship on their own behalf, and interruptible transportation is traded by hundreds of brokers. Cost of service rate regulation creates poor incentives on the part of the LDCs to lease or sell their transportation rights, since the revenue they gain from selling transportation will reduce what they are permitted to earn from selling gas.[17]

7.4 The Extent of the Gas Market

Spot prices at dispersed geographic locations became more highly correlated throughout the period from 1987 to 1990 as more pipelines became full fledged transportation firms. The correlations between prices at vertices that are circuitously-connected are nearly as high as correlations between prices at directly-connected vertices. Impulse response analysis shows that a price variation at a vertex is damped within a day at that vertex and within two days at every other vertex. Relative prices are independent of the vertex price chosen to be the numeraire price and of the day chosen—they would be the same if Houston or New York were the base and if Friday's relative prices were calculated from Monday's price levels at all the vertices. The competitive "law of one price" holds over the network and it holds in less than two business days.

The gas market is liquid: the percentage spread between the high and low prices in the most strongly connected subnetworks is about 6 per cent, which compares favorably with the bid–ask spread on organized stock exchanges. Another measure of liquidity is the amount of volume that can be bought or sold without a strong influence on prices. The daily data indicate that

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[17] Smith, De Vany, and Michaels (1991) propose an unregulated secondary market in transportation and devise the property rights to make transportation a tradeable commodity. A major pipeline proposed to implement a secondary market in transportation on its system, but the proposal was rejected by FERC (Transcontinental Gas Pipe Line Corporation, Federal Energy Regulatory Commission, Docket No. RP87–7–000, 1989).

the market can absorb sizeable daily or weekly variations in the volume of gas traded at any point without moving prices by more than a few points anywhere in the network. Given this high liquidity and smooth performance, one could index long-term gas contracts to the spot price in any of the spot markets scattered throughout the network. The liquid spot market could provide the basis for rebuilding the contract market which was unravelled in recent years by FERC orders which rescinded long term contracts.[18] The more strongly connected pipeline network that has emerged under open access makes new capacity that is added anywhere in the network available to increase the maximum network flow between any two vertices. In addition, the entire complex of producing fields becomes available as reserves against demands anywhere in the network.[19]

7.5 Markets versus Regulation

The analysis and evidence makes clear that in the brief period since FERC authorized markets they have flourished. Markets have come into existence in every field and at most major pipeline interconnections. The volume of gas transported has increased dramatically. Markets succeeded, where regulation failed, in equalizing gas prices across the geographically dispersed production fields. Because prices have been forced within arbitrage limits, the marginal value of natural gas, net of transmission cost, is approximately equal at each location and the allocation of gas has been improved.

Could prices have fallen so much if pipelines had not become contract carriers instead of merchant carriers? Spot markets came widely into existence only after transportation gave buyers access to the fields. The network interconnection points could not have become markets in the absence of transportation which permitted traders to interconnect pipelines. Transportation allowed spot gas to become a genuine alternative to contract gas. Because spot gas prices were market-driven, they put competitive pressure on contract prices and their decline led the decline of contract prices. Prior to Order 380, spot prices were higher than contract prices. After transportation became an option to gas buyers, spot prices (on average) declined to a level just

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[18] See Bradley (1991) and De Canio and Frech (1992) for a discussion of contracts that were abrogated by regulatory authority.

[19] See Mohring (1976) on how economies of massed reserved are gotten when small markets are integrated into one large market.

below the average contract price. After markets had become well-developed (about 1986 or 1987), contract and spot prices converged and moved closely together, though the spot price change leads the contract price change (as expected). There is more seasonality in prices than there was under regulated prices. Since regulated prices did not change over the season, it would be expected that market prices would be more seasonal than regulated prices. The good side of seasonal prices is that gas curtailments are less likely.

The seasonal pattern of prices presents new opportunities. As pipelines and local distribution companies bring additional storage on line, the seasonal pattern of prices will be smoothed. The gas futures market will further this process by spreading and shifting the risk of storing gas and by extending the ability of agents to contract over the season. The birth of the futures market shows that the network is sufficiently connected to ensure deliverability and liquidity in the contract. We do not know yet how effective the futures market has been in damping seasonal price swings. The visual evidence suggests there has been some smoothing. The ability to hedge inventory that has been provided by the futures market may lead to expanded gas storage.

The local distribution companies (LDCs) quickly seized on the opportunity to lower their delivered price of gas and become the major force behind the rapid conversion from pipeline system gas to transportation. The LDCs are the major buyers of gas, and it seems unlikely that spot prices could have converged so rapidly and completely without their participation. Brokers and the other players have contributed to disciplining gas prices. Competition to deliver gas has also promoted competition in transportation tariffs. There is no evidence of bottleneck monopolies.

Regulation continues to block the full development of markets and competition. The market in transportation could be made more efficient by making transportation rights fully transferable and subdividable as to injection and withdrawal points (Smith, De Vany, and Michaels (1988, 1991), and Transcontinental Gas Pipeline Company, 1989). Producers should be given the right to acquire firm transportation rights, either by contracting for new capacity or through purchase from a current holder of firm transportation. In light of the success of competition and markets in disciplining prices—where regulation failed—the lessons of open access should be applied to distributors and retail markets. The Natural Gas Act should be repealed to give markets the scope to operate efficiently and to empower gas users at all levels to make choice and competition the regulators of gas prices.

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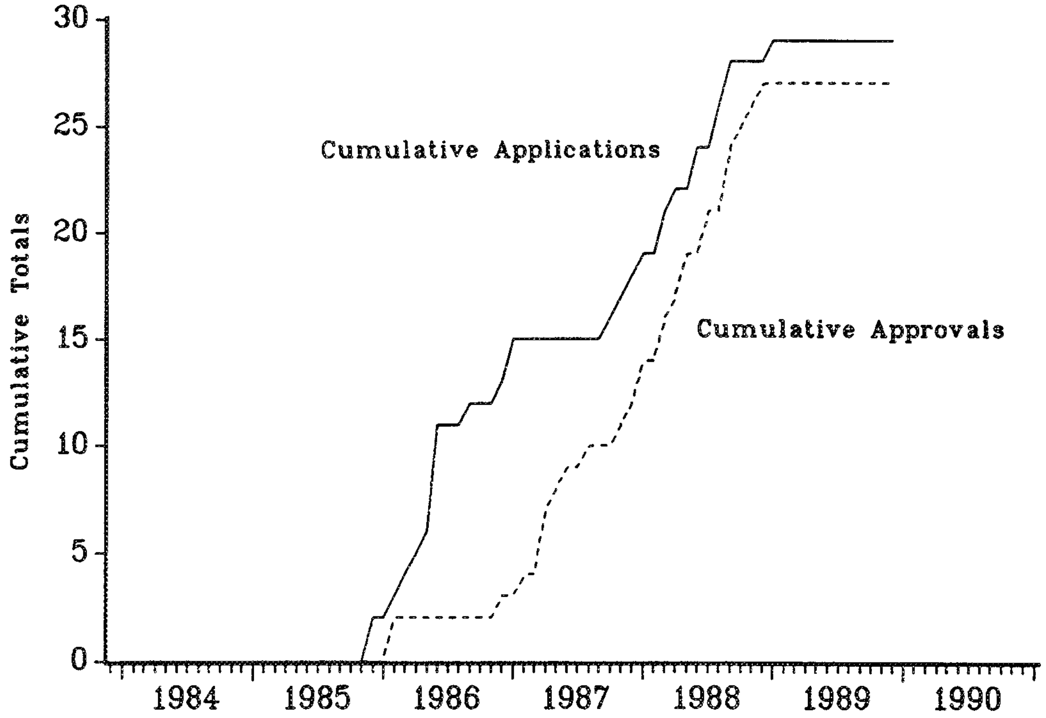
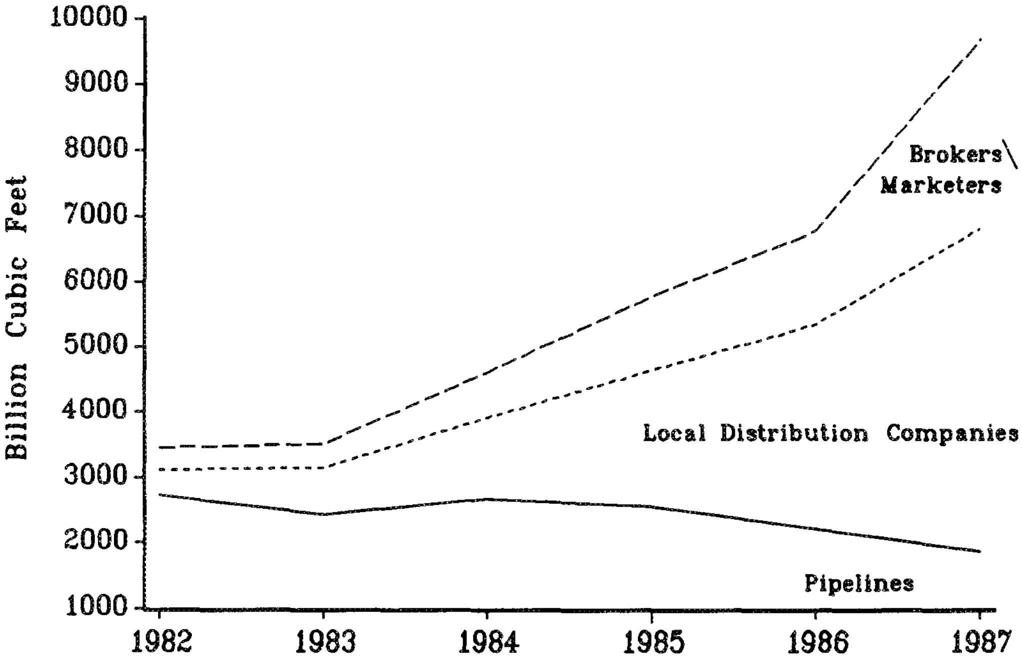
Transcontinental Gas Pipe Line Corporation, Federal Energy Regulatory Commission, Docket No. RP87–7–000 (1989).

Figure 1: Pipeline Applications/Approvals for Contract Carrier Status



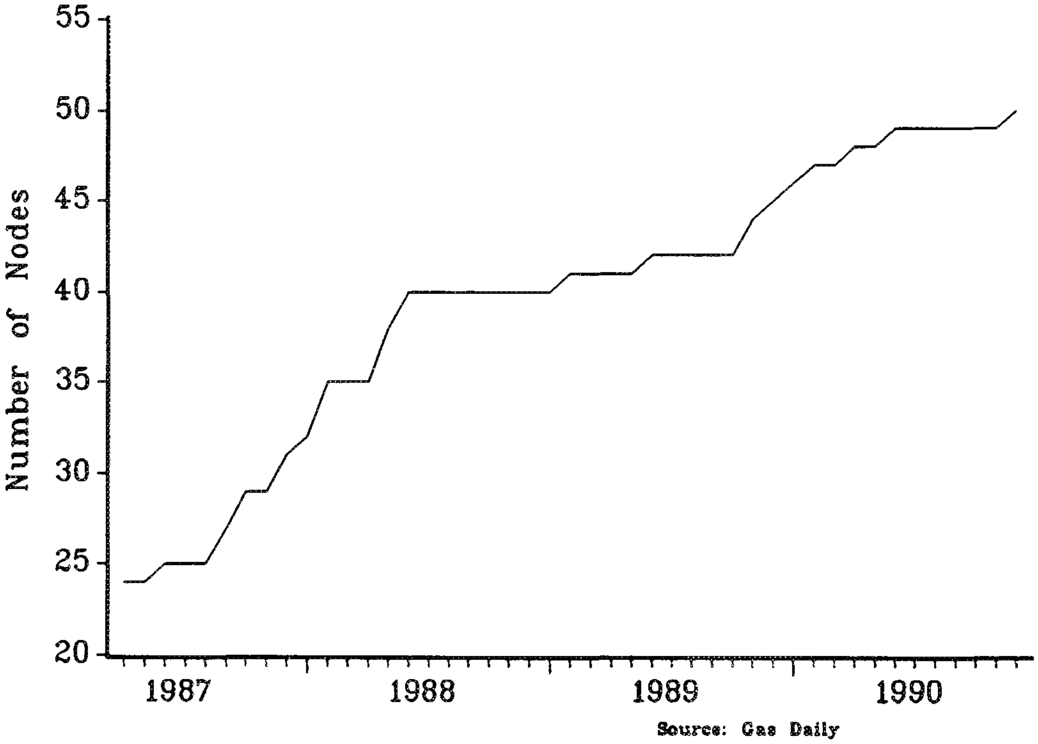
Source: FERC

Figure 2: Volumes Transported by User Category
(Billion Cubic Feet per Year)



Source: Energy Information Administration (1989).

Figure 3: Interconnection Nodes included in *Gas Daily's* price survey



Source: Gas Daily

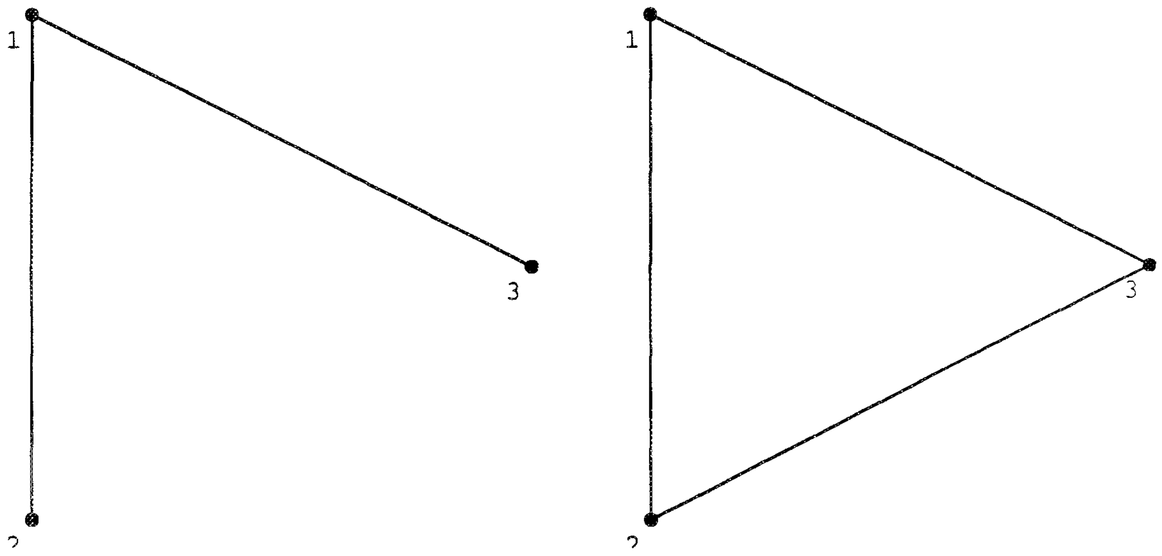


Figure 4: Disconnected and Connected Triangle Net Works

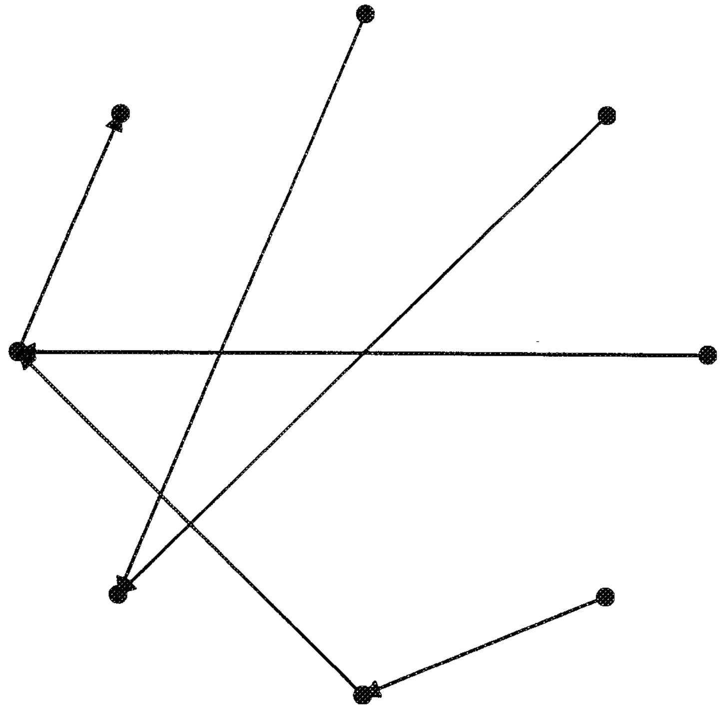


Figure 5: Net Work N

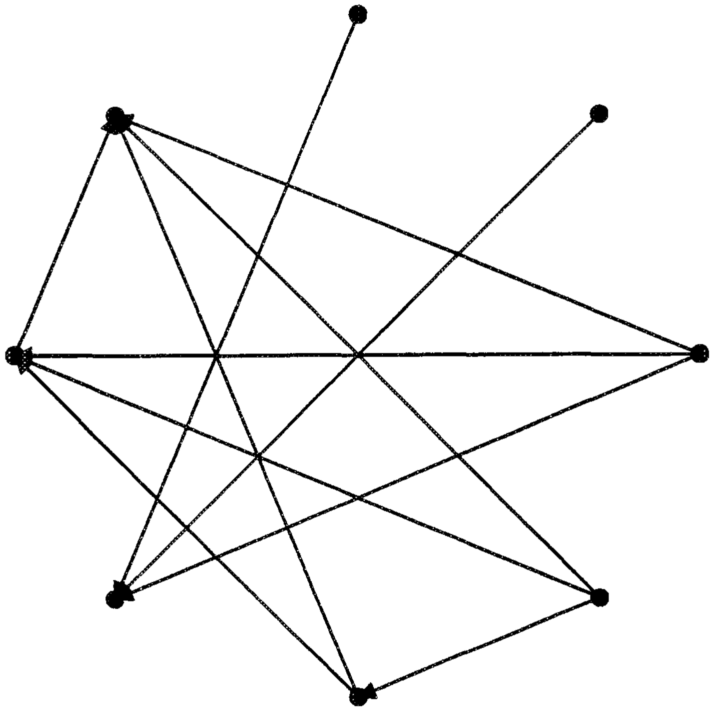
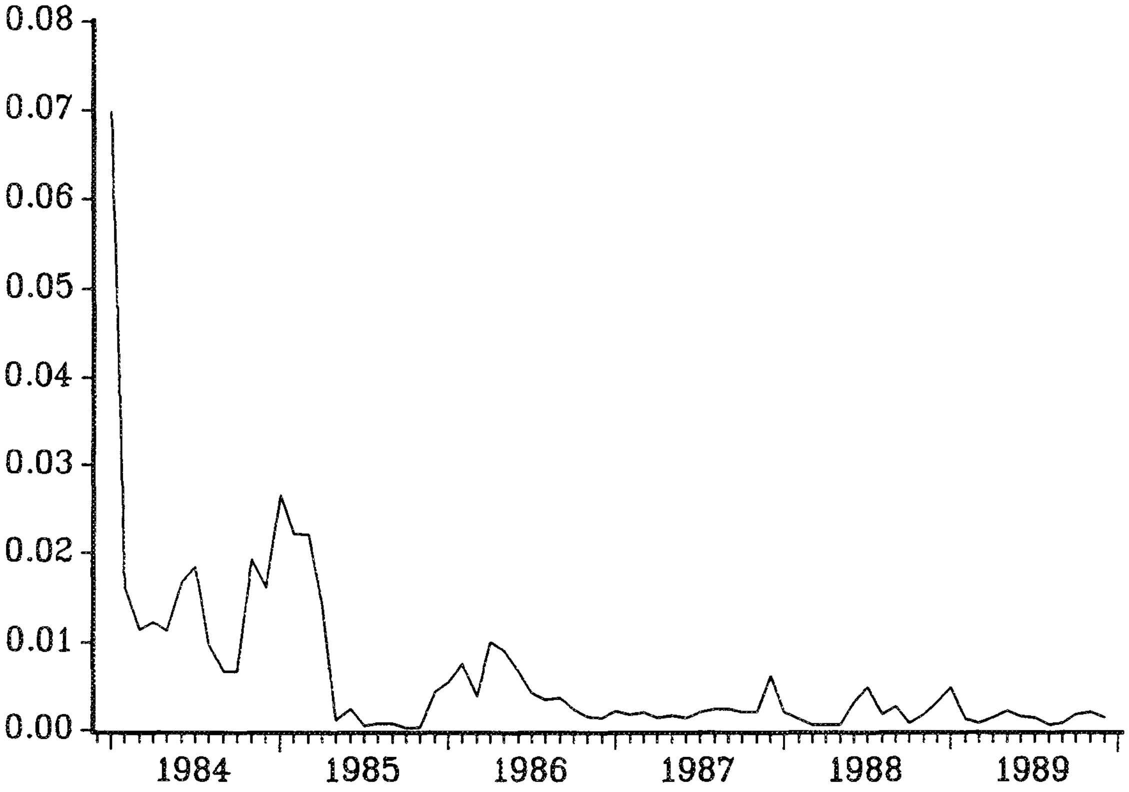


Figure 6: $\mathcal{C}(N)$:The Transitive Closure of N

Figure 7: Variance of Spot Prices across Regions



Source: Author's calculations

Figure 8: Natural Gas Spot Prices by Region

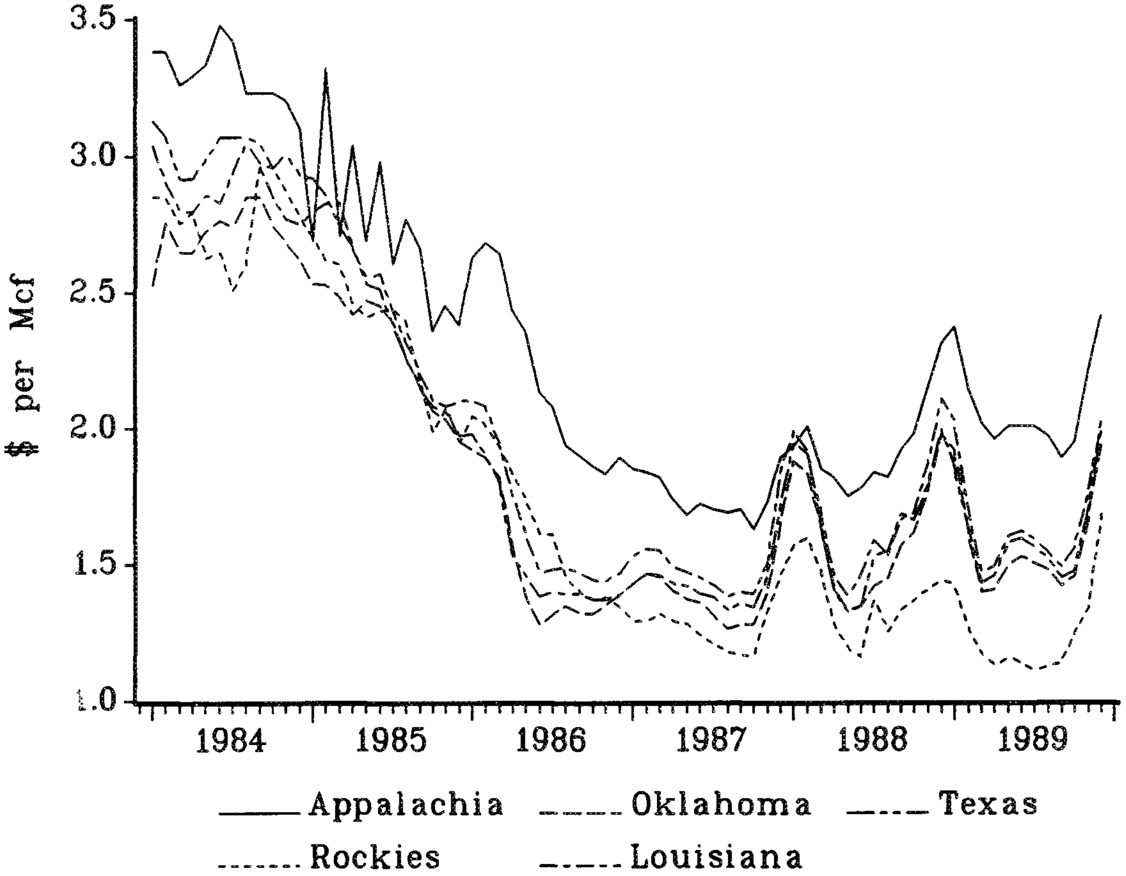


Figure 9: Bidweek High/Low/Average across the Network

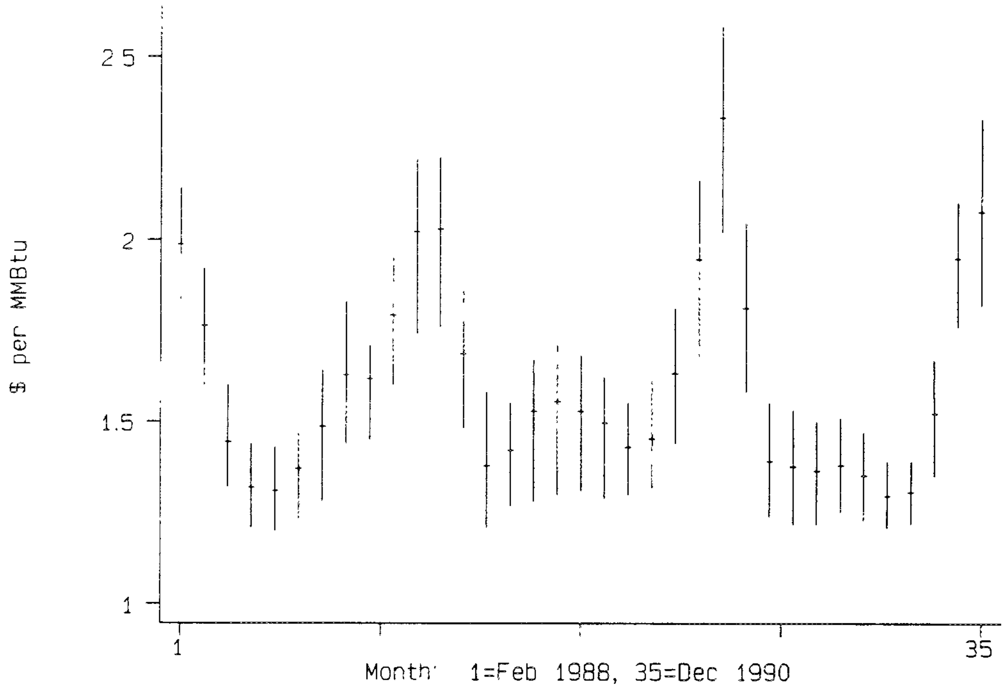
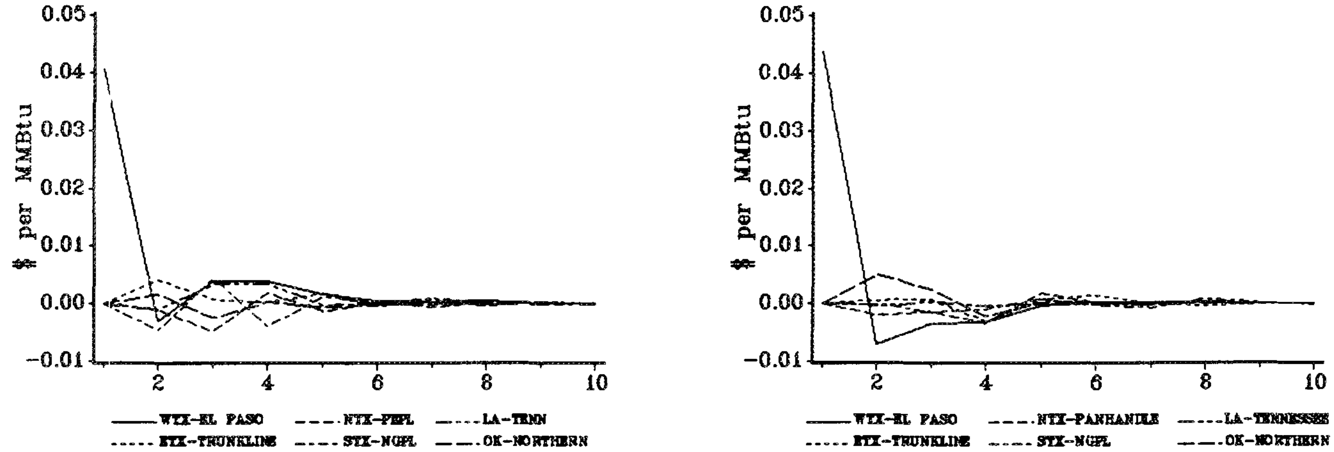


Figure 10: Response of Prices to Impulses

Estimation Period: July 1987 to June 1988

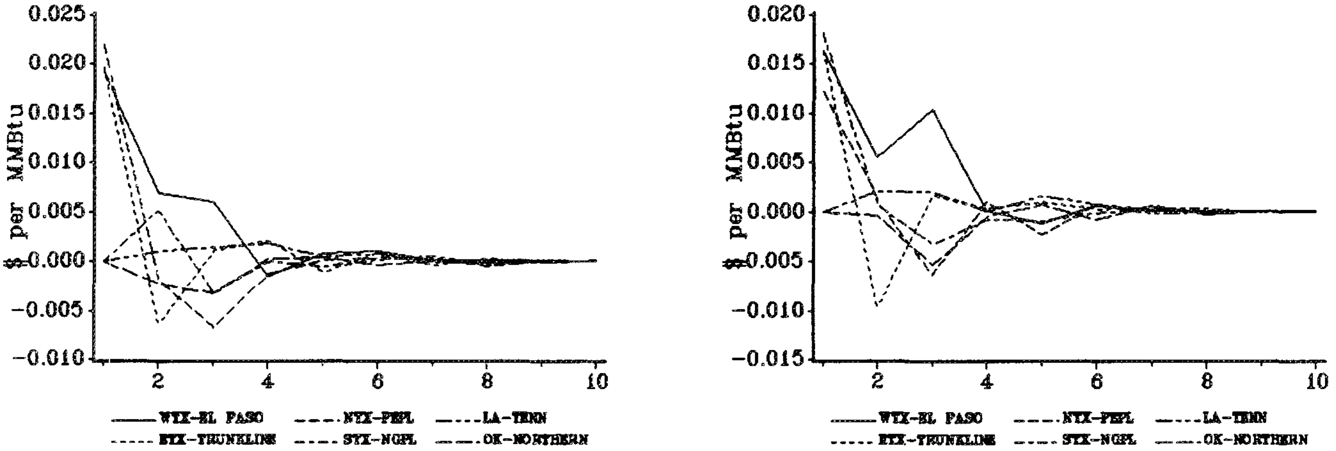
El Paso in West Texas

Trunkline in East Texas



Panhandle Eastern in North Texas

NGPL in South Texas



Tennessee Pipeline in Louisiana

Northern Pipeline in Oklahoma

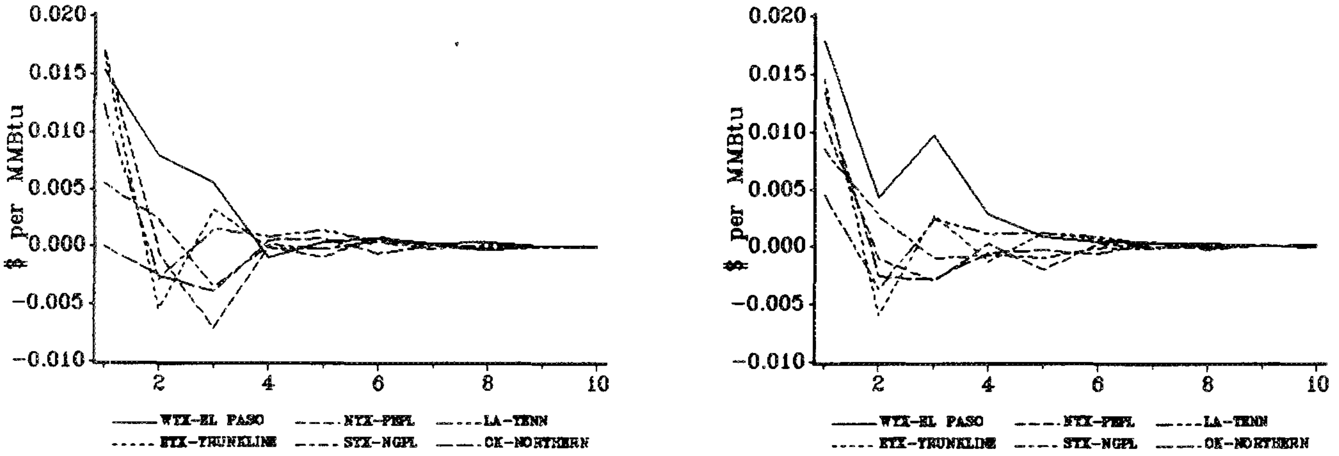
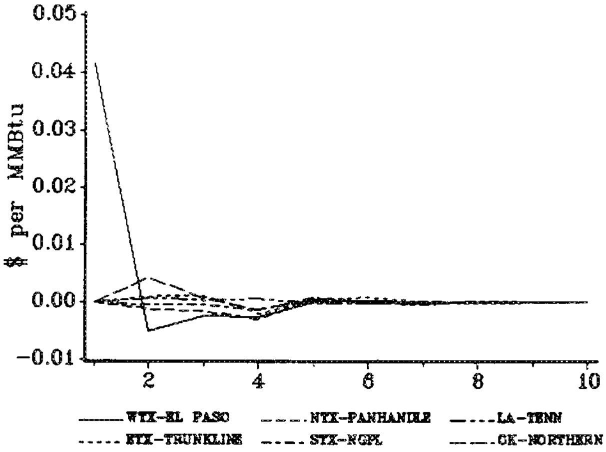


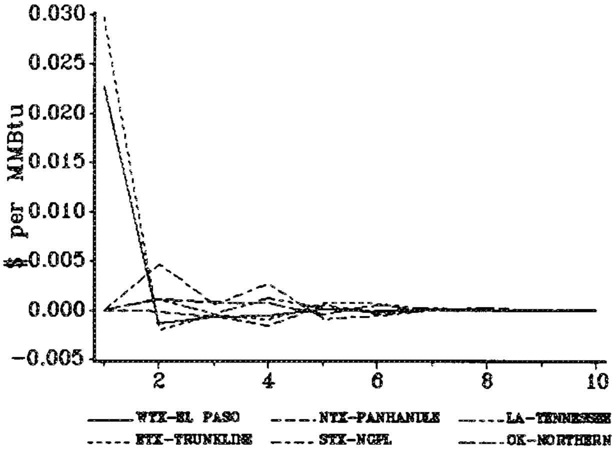
Figure 11: Response of Prices to Impulses

Estimation Period: July 1988 to June 1989

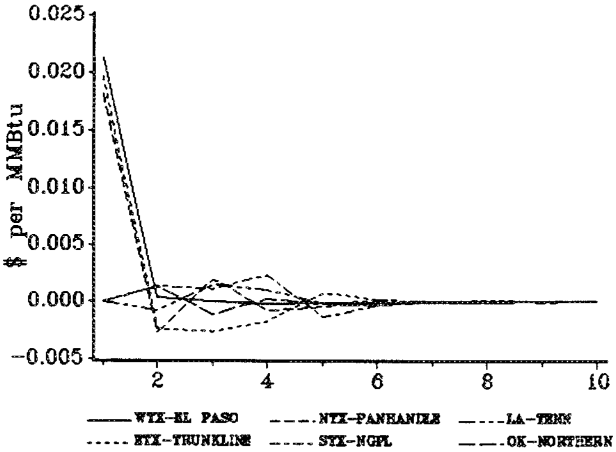
El Paso in West Texas



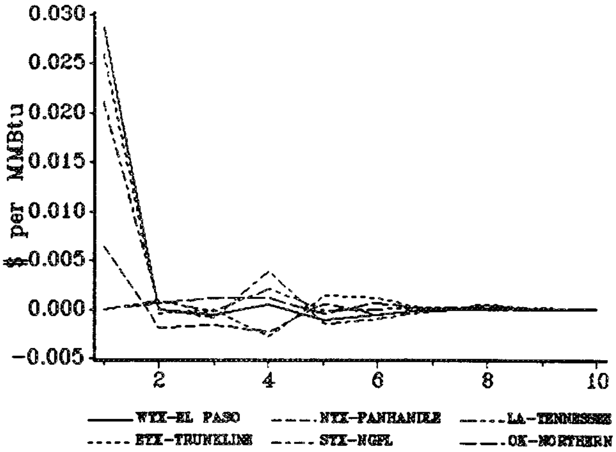
Trunkline in East Texas



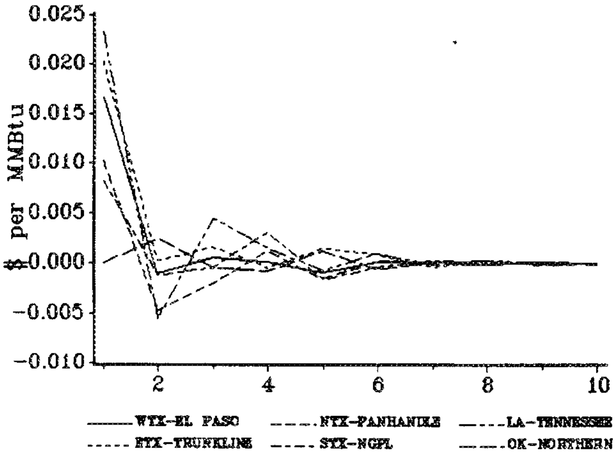
Panhandle Eastern in North Texas



NGPL in South Texas



Tennessee Pipeline in Louisiana



Northern Pipeline in Oklahoma

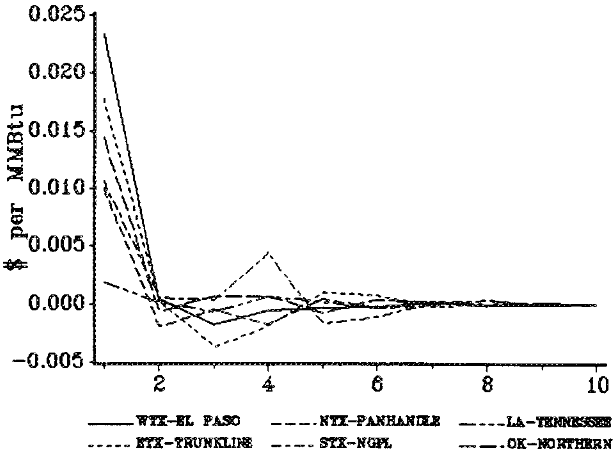


Figure 12: Response of Prices to Impulses

Estimation Period: July 1989 to June 1990

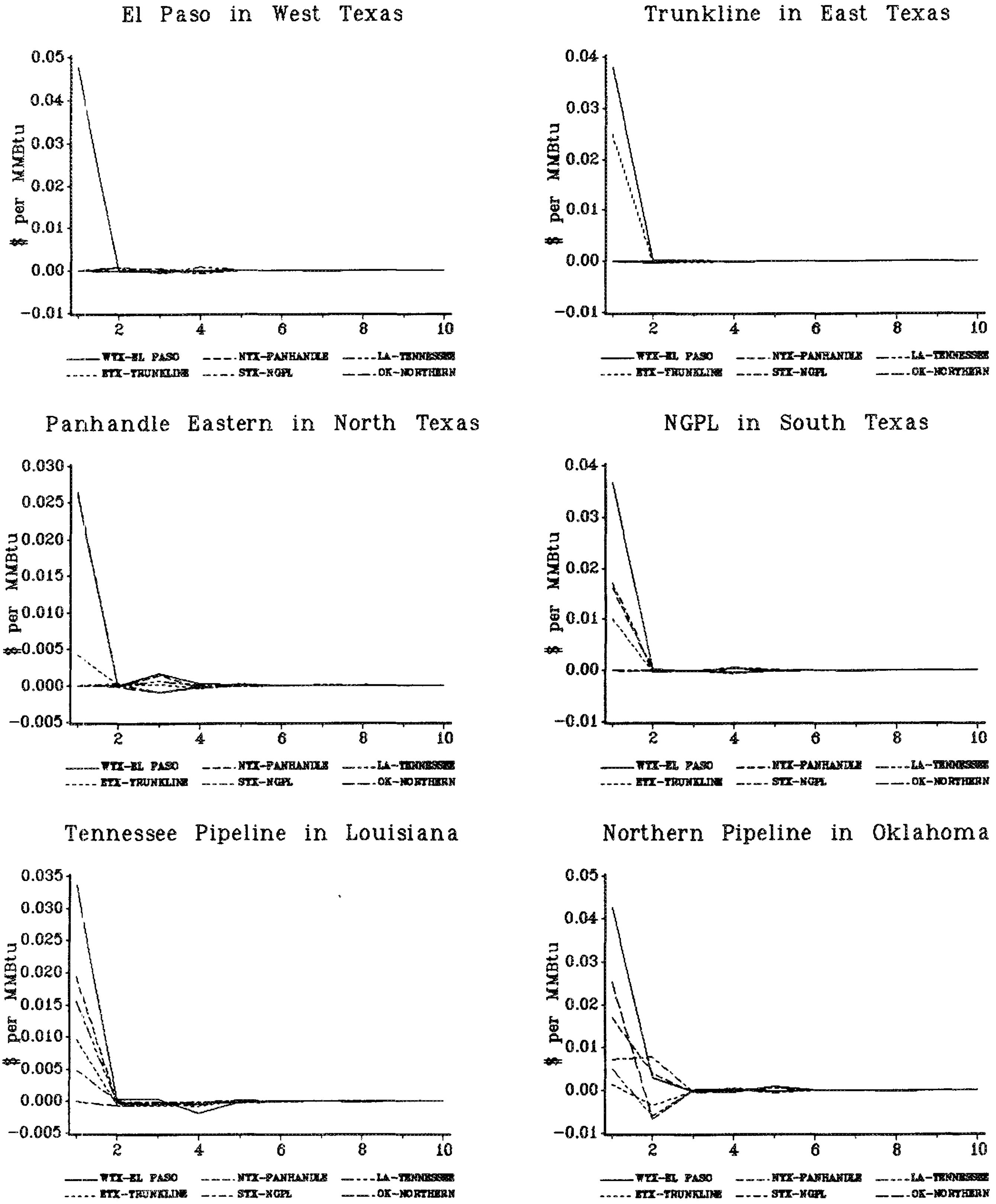


TABLE 1 - INTERCONNECTION NODES LISTED BY REGION AND PIPELINE

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 - Field—Level “No Arbitrage Opportunities” Test†

Injection Nodes	Regions	1987-88	1988-89	1989-90	1990-91	$\chi^2_{.05}$
Network 1						
El Paso	West Texas	268.40	192.80	84.53	309.50	134.35
Trunkline	East Texas					
Panhandle	North Texas					
NGPL	South Texas					
Tennessee	Louisiana					
Northern	Oklahoma					
Network 2						
El Paso	West Texas	256.05	232.29	11.60	126.69	134.35
NGPL	East Texas					
NGPL	North Texas					
NGPL	South Texas					
Tennessee	Louisiana					
NGPL	Oklahoma					
Network 3						
NGPL	East Texas	468.75	427.36	402.72	189.48	290.02
Tennessee	East Texas					
Trunkline	East Texas					
ANR	Louisiana					
Columbia	Louisiana					
Tennessee	Louisiana					
Texas Gas	Louisiana					
Trunkline	Louisiana					
United	Louisiana					
Network 4						
ANR	Louisiana	193.08	192.39	110.45	101.69	134.35
Columbia	Louisiana					
Tennessee	Louisiana					
Texas Gas	Louisiana					
Trunkline	Louisiana					
United	Louisiana					

† Likelihood Ratio χ^2 test statistics for $H_o : \gamma_{i,j,\ell} = 0 \ \forall i, j, \ell$