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Network Connectivity and Price Convergence: Gas Pipeline Deregulation

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Abstract

We use graph theoretic methods to model arbitrage on the evolving topology of the natural gas pipeline network following pipeline deregulation. We estimate models of spot prices over the network and show that the emergence, evolution and performance of natural gas spot markets are linked with the reorganization of natural gas pipelines brought about by the Federal Energy Regulatory Commission's policy of "Open Access". Under open access, the balkanized and disconnected network of gas markets created by regulation became more strongly connected, transportation markets developed, and natural gas spot prices converged. The pace of these changes can be linked to the degree of openness and connectedness of the pipeline network; it took four years for the network to reach a critical level of connectivity to bring convergence to prices. By 1990, gas markets had become thick enough to dampen the effect of demand and supply shocks on prices at each point in the network.

Key words: network connectivity, price convergence, gas pipeline deregulation, impulse response analysis.

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1 Introduction

Beginning in 1985, federal regulators allowed natural gas pipelines to unbundle natural gas from its transportation and to offer transportation service to their customers. These changes were implemented in the Federal Energy Regulatory Commission's Orders 436 and 500 which implemented the policy of "Open Access" of gas buyers and sellers to pipeline transportation. Open access authorized commodity and transportation markets as mechanisms for allocating and distributing natural gas. Open access permitted direct sales between producers and users of natural gas, which permitted spot markets to come forth. It placed transportation capacity in the hands of pipeline customers, which permitted a market for transportation to come forth. By opening individual links in the system and permitting trading in transportation, open access connected the U.S. pipeline network. We explore the significance of these changes theoretically and empirically.

We study how open access transformed the topology of the pipeline network. We show how the force of arbitrage in producing price convergence can be linked to the opening of the network and the degree of its connectivity. We first develop the idea of the topology of a market and use graph theoretic methods for modeling it. Then we analyze arbitrage on various topologies and show how prices depend on the graph-theoretic structure of the market. We then estimate properties of the network of natural gas spot markets and show how those properties evolved during the period from the beginning of Open Access to the present. We follow the evolution of daily spot prices in twenty markets as these markets progressively become embedded in a larger web of open pipelines and interconnected markets. We show that prices in these markets converge to arbitrage-free levels over time as they become more deeply embedded in a connected network of markets. The speed of convergence to arbitrage-free prices is linked to the topology of the network (measures of connectivity and market depth or volume of trading).

The 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. The transition was not gradual or continuous; there was a sharp transition when network connectivity reached a critical level. Four years after regulators authorized gas markets, competition was enforcing the law of one price.

2 Pipeline Institutions

Under the Natural Gas Act, Congress re-organized the industry as a system of separate merchant carrier pipelines. Vertical integration was discouraged, entry was controlled, and pipeline tariffs and gas prices were regulated (Mulherin, 1986a, 1986b). 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.

Open Access changed the organization of the pipeline by reallocating transportation capacity from the pipeline to its customers.[1] There are now many

[1] 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 174% (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, 1991). Pipelines' business shifted rapidly from selling gas to transporting it for others (De Vany and Walls, 1993b; Energy Information Administration, 1989).. As

suppliers of transportation and, within regulatory limits, they can exchange their firm transmission rights among themselves or transfer them to brokers and third parties; a limited market has come forth for pipeline transportation. By opening the transportation system to pipeline customers, open access made possible the creation of a connected pipeline grid.[2] Customers and brokers are able to exchange and combine transportation rights, and use this method to create connected network topologies over which they can effect arbitrage. A trading network can be constructed by combining transmission rights on several pipelines.

A transaction for gas specifies a volume, 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. A transportation contract specifies injection and withdrawal points and maximum volumes.[3] The spot contracts in the gas commodity market are for volumes to be delivered to a specific injection point on the pipeline system. From this point, customers exercise their transmission right and withdraw the gas from the pipeline at the downstream destination.

Open access has had a profound effect on the natural gas industry.[4] It transformed the old regulatory system of protected natural monopoly pipelines functioning as merchant carriers buying, selling and delivering gas bundled with transportation under a regime of regulated pipeline tariffs into a market-driven system. Markets emerged and rapidly grew in number. Pipelines quickly became transporters rather than sellers of gas and long-term contract sales of gas gave way to spot sales. This story has been told in a number of places,[5] but the importance of open access in promoting the formation of an interconnected pipeline grid has not been fully explored and developed. We show that the regulatory system balkanized gas markets by creating a system of individual and protected pipelines that were not interconnected with one another. Open access opened not only individual links in the network, but promoted the emergence of a strongly interconnected network. This transformation of the topology of the pipeline network was a critical factor in promoting convergence of spot prices.

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open access spread through the pipeline network, spot markets quickly opened at fields and interconnection points (De Vany and Walls, 1993b).

[2]There are 21 major interstate pipelines and 1400 local distributors who hold transportation capacity on the major pipelines (Bradley, 1991). Gas users or other parties can purchase gas from all the fields to which they can obtain direct or indirect connections. Holders of firm transportation contracts may trade with one another or transfer their rights to brokers and other parties. However, the regulatory commission has not permitted transportation to become a fully transferable property right.

[3]Pipelines coordinate their customers' transmission demands during what is called "bid-week." 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. During the bidweek, gas users who hold capacity rights purchase the volumes which they nominate for transmission during the following month.

[4]Prior research on the natural gas industry has usually focused on long-term contracts (see, for example, Masten and Crocker (1985), Mulherin (1986a, 1986b), Masten (1988), and Hubbard and Weiner (1986, 1991)). In contrast, our research looks at how opening up the pipeline system to transportation led to the emergence of spot markets, price convergence and, to a large extent, the dissolution of the long-term contract market (Bradley, 1991).

[5]See, for example, Smith et al. (1988), Walls (1992), and De Vany and Walls (1993a, 1993b).

3 Exchange, Connectivity, and Convergence

3.1 Arbitrage in a Simple Pipeline Network

Consider the simple system shown in Figure 1 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. We can represent this system by the accessibility matrix of its graph; for the system shown in Figure 1, the accessibility matrix is a three by three matrix with a 1 where there is an edge connecting points and a 0 where there is no connecting edge. Since 1 and 2 are connected and 1 and 3 are connected, 2 and 3 are not connected, and each point is accessible to itself, the accessibility matrix is:

$$\begin{matrix} 1 & 1 & 1 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{matrix} \tag{1}$$

The significance of this regulated structure lies in three features:

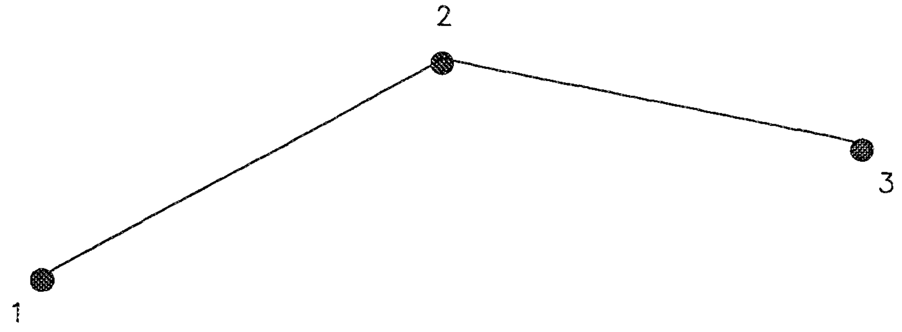
- There is a single supplier at point 1— the pipeline as merchant selling gas bundled with transport. Gas buyers do not buy directly from suppliers, of which there are many.
- Gas buyers at points 2 and 3 cannot trade with one another: 2 cannot ship to 3 and 3 cannot sell gas at 2 even though it is flowing past 2 on the way to 3.
- Buyers at points 2 and 3 cannot resell the gas they buy from pipeline back into the market at point 1.

The important features of open access and unbundling are those that transform these structural features to open up the options of gas buyers and sellers and permit arbitrage to operate over this small network. Consider how unbundling and open access change the accessibility matrix: Under open access the accessibility matrix becomes

$$\begin{matrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{matrix} \tag{2}$$

The diagonal and first row of the matrix is as before: each point remains accessible to itself, and a user at either 2 or 3 can buy gas from a supplier at 1 and transport it to 2 or 3. The last term in the second row indicates that a trader can now take gas delivered to 2 and sell and deliver it to point 3. The first term of the second row represents a more complicated transaction: it says gas can be sold from point 2 back to point 1, even though it is against the flow of the pipeline. This kind of trade may be called a "backhaul" or an "offset". It works because the gas that would be sent to point 2 can be delivered somewhere

Figure 1: A Simple Pipeline Network



upstream of point 2 as a backhaul transaction or it can be sold to another buyer in the producing area as an offsetting trade or sale. Similarly, as row three of the accessibility matrix indicates, 3 can backhaul or offset transactions at 1 and 3 can sell gas at 2. Not only is the space of transactions widened by open access, the parties with whom one can transact is enlarged. Each buyer has access to every supplier at all the points in the network, including the original pipeline-merchant. The sparse accessibility matrix of the balkanized, regulated industry structure is contained in the open access accessibility matrix, which is populated by points everywhere in the network. This property of containment is crucial to our analysis for we analyze a sample of markets that becomes more deeply embedded in a network of markets over time; its matrix represents a small network of interconnected markets which is contained in a larger sparse matrix which represents the national grid. Over time, the submatrix fills in with more 1's and the larger matrix becomes less sparse so that many more connections between markets become possible.

3.2 Network Connectivity and Price Convergence

Now consider a larger network which is more representative of the gas pipeline network. Denote the network $\mathcal{N}$. The production fields, pipeline hubs, and the city markets are elements of the set of vertices V of $\mathcal{N}$ and the arcs A of the pipeline network are the ordered pairs of the elements of V. If there is a directed arc from i to j, then j is said to be accessible to i and the i,j entry of the accessibility 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.

We are interested in characterizing the structure of prices over the network as it is transformed from a closed, disconnected system to a system of open access, connected pipelines. Each new open access pipeline forms a connected subnetwork of the larger network; as more pipelines become open access transporters, the larger network becomes more connected because the subnetworks are joined. This means gas buyers and sellers can ship over a wider area and gain access to a larger space of transactions.

We represent the spatial links over which trades can be made by putting 1's or 0's in the accessibility matrix. A network is connected if there is a path (a sequence of arcs) between all of its vertices. When a pipeline opens access to transportation, all of its points are strongly connected, meaning there is a direct path between every vertex. The national network is connected if all of its subnetworks are connected and its degree of connection is roughly the number of its subnetworks that are connected. The evolution of transportation in the network can then be characterized by the evolution of its accessibility matrices over time:

$$A_{t=0}(\mathcal{N}) \subseteq A_{t=1}(\mathcal{N}) \subseteq \dots \subseteq A_{t=T}(\mathcal{N}). \tag{3}$$

Initially, $A_t(\mathcal{N})$ is sparsely populated with 1's, representing the closed merchant system of bundled transportation. As more pipelines open access to transportation, the matrix becomes more densely populated with 1's and the space over which spot transactions can be made widens. Components in the network become strongly connected and form trading areas within the larger system. Each new matrix contains the old matrix as a subset. If, eventually, all pipelines open access to transportation, the network becomes fully connected.[6]

[6] Looking ahead to the empirical results, Table 1 gives some sense of the evolution of the network in the years following the FERC's open access ruling. It shows the dates at which major pipelines applied for and received approval to became open access pipelines.

How do new links in the network affect the total number of paths over which trading could proceed? We use the following theorem from graph theory to compute the number of paths of various distances between the points in the network: The number of paths of distance $D_1, D_2, \ldots, D_{n-1} \leq D$ in the network $\mathcal{N}$ connecting vertices i, j is given by the i, j-th entry in the $n \times n$ matrix $A^D(\mathcal{N})$. By applying this theorem, we calculated the number of paths of length 1 and length 2 between the vertices of the pipeline network for 1986 and late 1988 with the results shown in Figure 2. The points are numbered from 1 to 20 on the horizontal axis and the numbers of paths of length 1 and 2 for 1986 and 1988 are on the vertical axis. For these purposes the number of points reachable by a path of length one represents all the paths from other markets to the market on the horizontal axis that use just one link in the transmission system; the paths between markets reachable by using two links are similarly defined. It is apparent that in 1986, many of the 20 markets could be reached by a path one link long and by 1988 most of them could be reached in one link; those that could not lay two or more links away. The zero points on the graph indicate markets unreachable by length one or length two paths. By 1988, most of the pipelines were open and all but two markets were reachable by at least 50 paths from other markets. The markets at locations 3 through 5 are "hubs" that lie at the center of a highly connected portion of the grid; they are connected by over 120 paths to markets just two links away. This means there are over 120 arbitrage paths from other markets to these.

As more connections are formed by open access pipelines, the number of vertices connected by at least one path of length $\leq D$ increases faster than the square of the number of arcs. This follows because the row sum of $A^D(\mathcal{N})$, 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 n by n network, every entry of $A^D(\mathcal{N})$ is non-zero for every path length $D \leq n$.

We now relate the connectivity of the network to the number of competitive pricing constraints at each vertex and show that prices converge as the network becomes strongly connected. Consider prices in a network $\mathcal{N}$ with vertices and arcs (V, A). Let $\mathcal{P}(V, A)$ be the ordered set of equilibrium vertex prices. Let the number of arcs connecting the vertices of $\mathcal{N}$ increase with no change in the vertices of the network; then the arcs at time $t = 1, \ldots, T$ are related as the evolution of their accessibility matrices:

$$A_0(\mathcal{N}) \subseteq A_1(\mathcal{N}) \subseteq \ldots \subseteq A_T(\mathcal{N}). \tag{4}$$

The price set is (weakly) decreasing as the number of arcs grows because the number of binding constraints on prices is non-decreasing as the number of connected arcs increases, so

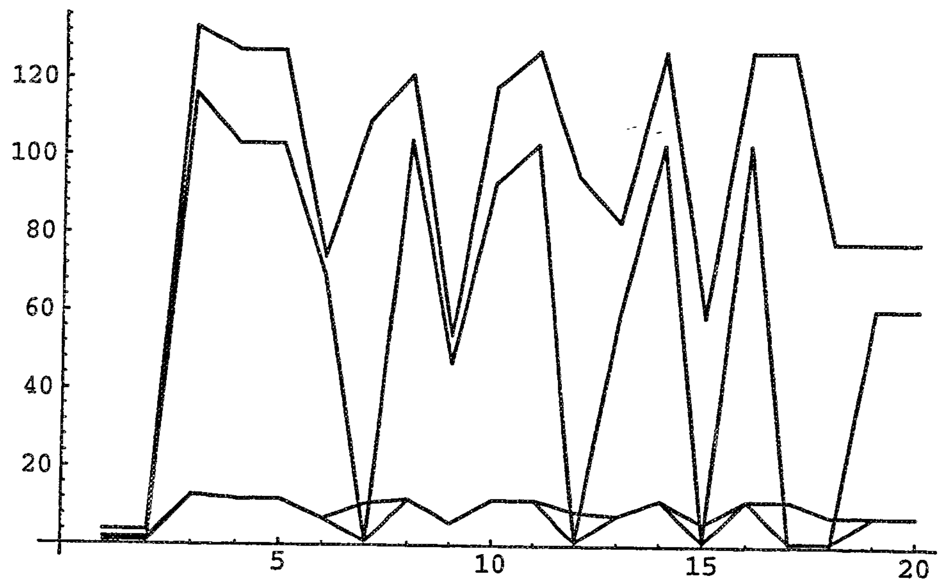
$$\mathcal{P}(V, A_0) \supseteq \mathcal{P}(V, A_1) \supseteq \ldots \supseteq \mathcal{P}(V, A_T). \tag{5}$$

The price set shrinks as the number of arcs grows because the number of competitors becomes larger and the minimum shipping distances between vertices shrink.

3.3 The Network Pricing Hypothesis

When traders transact in the open access pipeline network, they cause the price of gas at each location to reflect its value at each other node throughout the

Figure 2: Number of Paths of Lengths One and Two in 1986 and 1988 Networks



network. If prices at each node reflect all information in the network at each point in time, and all arbitrage possibilities 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, consider a pipeline network that links N distinct vertices. Let $i \in [1, N]$ index the vertices and denote the price of gas at vertices i and j at time $t-1$ as $p_{i,t-1}$ and $p_{j,t-1}$, respectively. If $p_{i,t}$ is predicted better by $p_{j,t-1}$ than by $p_{i,t-1}$, then there exists an unexploited arbitrage opportunity between the two nodes. A trader could buy gas at node j and sell gas at node i to exploit the opportunity. Predictable relationships between relative prices cannot exist if the network is fully arbitraged; an arbitrageur would exploit the difference in relative prices and cause the profitable opportunity to dissipate.

This 'no arbitrage possibilities' idea can be made more explicit by modeling the price at each vertex as a function of the the previous day's price at that vertex and exogenous factors. Let $\mu_{i,t}$ be a white noise process at node i that may be contemporaneously correlated with the white noise at other nodes. Further, let W_t represent an exogenous factor (such as the weather) that affects prices at each node. We can write this as

$$
\begin{aligned}
p_{1,t} &= \omega_1 W_t + p_{1,t-1} + \mu_{1,t} \\
&\vdots \\
p_{i,t} &= \omega_i W_t + p_{i,t-1} + \mu_{i,t} \qquad (6) \\
&\vdots \\
p_{N,t} &= \omega_N W_t + p_{N,t-1} + \mu_{N,t}.
\end{aligned}
$$

These equations can be rewritten by taking first differences, where $\triangle p_{i,t} = p_{i,t} - p_{i,t-1}$.[7] Taking first differences, each of the resulting time series ($\triangle p_{i,t}$) is the sum of the exogenous factor W_t and the white noise process μ_t: $\triangle p_{i,t} = \omega_i W_t + \mu_{i,t}$.

There are two dimensions in which to test the hypothesis of no exploitable arbitrage possibilities: over time and across the network. For the hypothesis not to be rejected, the first differences of prices at each node in the network cannot depend on the past price differences for that node, nor for any other node. Let $\ell \in [1, \mathcal{L}]$ denote the temporal lag of a variable. The 'no arbitrage opportunities' hypothesis can be tested by estimating the following system of equations.

$$
\begin{aligned}
\triangle p_{1,t} &= \omega_1 W_t + \gamma_{1,1,0} + \textstyle\sum_{\ell=1}^{\mathcal{L}} \sum_{j=1}^{N} \gamma_{1,j,\ell} \triangle p_{j,t-\ell} + \mu_{1,t} \\
&\vdots \\
\triangle p_{i,t} &= \omega_i W_t + \gamma_{i,i,0} + \textstyle\sum_{\ell=1}^{\mathcal{L}} \sum_{j=1}^{N} \gamma_{i,j,\ell} \triangle p_{j,t-\ell} + \mu_{2,t} \qquad (7) \\
&\vdots \\
\triangle p_{N,t} &= \omega_N W_t + \gamma_{N,N,0} + \textstyle\sum_{\ell=1}^{\mathcal{L}} \sum_{j=1}^{N} \gamma_{N,j,\ell} \triangle p_{j,t-\ell} + \mu_{N,t}
\end{aligned}
$$

If any one of the $\gamma_{j,i,\ell}$ is nonzero, this indicates that the price change at node i during the ℓ'th previous time period can predict the current price change at node j for the current time period. A trader could exploit this predictability by buying gas at one node and selling it at another, possibly through some

[7] We take first differences to make each price series stationary. The results of Dickey-Fuller unit root tests on each price series are presented with the empirical results in Section 4.

complex sequence of transactions. In the formulation above, the test for arbitrage opportunities is across N nodes for each of $\mathcal{L}$ lags. This allows for a large number of arbitrage possibilities.[8] Testing the arbitrage pricing hypothesis is equivalent to testing the joint hypothesis that each of the $N \times (N \times \mathcal{L} + 1)$ γ's is equal to zero. The test statistic, which is based on the likelihood ratio, is computed directly from the log determinant of the residual series for the model estimated with and the without the restrictions imposed on the γ's.[9] Let T be the number of observations, r the number of γ's that are restricted to be equal to zero, and let Σ_R and Σ_U represent the covariance matrices for the restricted and unrestricted models, respectively. The likelihood ratio test statistic, which is distributed chi-squared with r degrees of freedom, can be computed directly from the residual covariance matrices as

$$T(\ln \mid \Sigma_R \mid - \ln \mid \Sigma_U \mid) \sim \chi^2(r). \tag{8}$$

A large value of the test statistic indicates that arbitrage opportunities have not been fully exploited.

4 Data and Empirical Evidence

Gas Daily reports 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 pipelines, or at the interconnection of several major pipelines. Our sample includes twenty vertices for which *Gas Daily* has continuously reported daily spot prices since July 1987. 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 shows what regions and pipelines are in the sample and when the pipelines opened to transportation (both application and approval dates are shown). Corresponding to these changes in the network are the number of points to which each point can ship gas (out degrees) and the number of sources that can ship gas into that point (in degrees).

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 stated in dollars per million Btu ($/MMBtu) for spot contracts of 30 days or less.

For our empirical analysis, we partitioned the data into three equal subsamples: 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 1) each period begins and ends in an off-peak period, and 2) so that we can evaluate changes in the model's estimates and convergence properties over the interval from July 1987–June 1990.

[8]This vector autoregression model has few restrictions placed upon it. In fact, with ten nodes in the network and three time lags there are 320 γ's to be estimated; each γ corresponds to a unique arbitrage possibility.

[9]See Harvey (1991, pp. 340–341) for a discussion of hypothesis testing in multivariate time series models and for the derivation of the test statistic.

Table 1: Pipeline Application and Approval Dates for Open Access

Region	Pipeline	Application	Approval
West Texas	El Paso	6/88	11/88
West Texas	Transwestern	12/87	3/88
East Texas	NGPL	6/86	5/87
East Texas	Tennessee	12/86	6/87
East Texas	Trunkline	6/86	4/87
East Texas	Panhandle	6/86	11/87
North Texas	ANR	6/88	7/88
North Texas	NGPL	6/86	5/87
North Texas	Northern	6/86	1/88
South Texas	NGPL	6/86	5/87
South Texas	Tennessee	12/86	6/87
Louisiana	ANR	6/88	7/88
Louisiana	Columbia	12/85	2/86
Louisiana	Tennessee	12/86	6/87
Louisiana	Texas Gas	8/88	9/88
Louisiana	Trunkline	6/86	4/87
Louisiana	United	10/87	1/88
Oklahoma	ANR	6/88	7/88
Oklahoma	NGPL	6/86	5/87
Oklahoma	Northern	6/86	1/88

Source: Energy Information Administration (1989).

Table : Unit Root Tests on Daily Price Series: July 1987 - June 1988

$$\Delta p_t = \phi p_{t-1} + \sum_{\ell=1}^{\mathscr{L}} \beta_\ell \Delta p_{t-\ell} + \mu_t$$

	$\mathscr{L} = 1$		$\mathscr{L} = 4$	
Node	$\hat{\phi} \times 10^3$	t	$\hat{\phi} \times 10^3$	t
West Texas				
El Paso	-0.257	-0.150	-0.390	-0.226
Transwestern	-2.745	-1.431	-2.766	-1.335
East Texas				
NGPL	0.185	0.123	0.155	0.099
Tennessee	-0.085	-0.064	-0.096	-0.070
Trunkline	-0.299	-0.177	-0.317	-0.185
North Texas				
ANR	-1.788	-1.493	-2.097	-1.598
NGPL	-0.530	-0.336	-0.533	-0.329
Northern	1.394	1.325	1.373	1.193
Panhandle	-0.260	-0.154	-0.261	-0.152
South Texas				
NGPL	-0.033	-0.021	-0.036	-0.022
Tennessee	-1.490	-1.151	-1.612	-1.167
Louisiana				
ANR	-0.095	-0.062	-0.081	-0.052
Columbia	-0.168	-0.125	-0.166	-0.123
Tennessee	-0.051	-0.036	-0.051	-0.036
Texas Gas	-0.228	-0.142	-0.238	-0.148
Trunkline	-0.279	-0.162	-0.261	-0.151
United	-0.231	-0.134	-0.228	-0.128
Oklahoma				
ANR	-0.631	-0.339	-0.620	-0.324
NGPL	-0.228	-0.143	-0.229	-0.143
Northern	-0.436	-0.291	-0.437	-0.291

MacKinnon Critical Values for the t-statistics: -2.574 (1%); -1.941 (5%); -1.616 (10%).

Table 2: Unit Roots Tests on Price Series, 1987–88

Table : Unit Root Tests on Daily Price Series: July 1988 - June 1989

$$\Delta p_t = \phi p_{t-1} + \sum_{\ell=1}^{\mathscr{L}} \beta_\ell \Delta p_{t-\ell} + \mu_t$$

	$\mathscr{L} = 1$		$\mathscr{L} = 4$	
Node	$\hat{\phi}$ x 10^3	t	$\hat{\phi}$ x 10^3	t
West Texas				
El Paso	0.138	0.084	0.347	0.214
Transwestern	0.256	0.254	0.460	0.460
East Texas				
NGPL	0.476	0.254	1.140	0.591
Tennessee	-0.140	-0.092	-0.175	-0.112
Trunkline	0.202	0.132	0.507	0.325
North Texas				
ANR	-0.052	-0.031	-0.041	-0.024
NGPL	-0.165	-0.074	-0.313	-0.138
Northern	0.266	0.152	0.359	0.206
Panhandle	0.062	0.036	0.125	0.723
South Texas				
NGPL	0.442	0.244	0.828	0.444
Tennessee	0.399	0.259	0.367	0.232
Louisiana				
ANR	0.189	0.144	0.217	0.164
Columbia	0.275	0.212	0.272	0.207
Tennessee	0.264	0.189	0.235	0.167
Texas Gas	0.299	0.196	0.336	0.218
Trunkline	0.118	0.086	0.176	0.127
United	0.210	0.125	0.189	0.116
Oklahoma				
ANR	0.004	0.003	0.004	0.003
NGPL	-0.376	-0.194	-0.355	-0.178
Northern	0.116	0.078	0.168	0.112

MacKinnon Critical Values for the t-statistics: -2.570 (1%); -1.941 (5%); -1.616 (10%).

Table 3: Unit Roots Tests on Price Series, 1988–89

Table : Unit Root Tests on Daily Price Series: July 1989 - June 1990

$$\Delta p_t = \phi p_{t-1} + \sum_{\ell=1}^{\mathcal{L}} \beta_\ell \Delta p_{t-\ell} + \mu_t$$

	$\mathcal{L} = 1$		$\mathcal{L} = 4$	
Node	$\hat{\phi} \times 10^3$	t	$\hat{\phi} \times 10^3$	t
West Texas				
El Paso	-0.698	-0.382	-0.709	-0.388
Transwestern	-0.868	-0.426	-0.879	-0.433
East Texas				
NGPL	-1.016	-0.572	-1.001	-0.561
Tennessee	-0.653	-0.423	-0.639	-0.410
Trunkline	-0.754	-0.431	-0.749	-0.428
North Texas				
ANR	-0.438	-0.255	-0.447	-0.259
NGPL	-0.739	-0.343	-0.739	-0.341
Northern	-1.183	-0.504	-1.183	-0.501
Panhandle	-0.503	-0.307	-0.510	-0.310
South Texas				
NGPL	-0.664	-0.378	-0.664	-0.376
Tennessee	-1.175	-0.687	-1.183	-0.689
Louisiana				
ANR	-0.704	-0.424	-0.689	-0.418
Columbia	-0.704	-0.405	-0.698	-0.399
Tennessee	-0.665	-0.411	-0.658	-0.405
Texas Gas	-0.652	-0.445	-0.636	-0.435
Trunkline	-0.784	-0.402	-0.803	-0.414
United	-0.878	-0.489	-0.859	-0.478
Oklahoma				
ANR	-0.558	-0.317	-0.558	-0.315
NGPL	-0.715	-0.340	-0.715	-0.338
Northern	-0.971	-0.419	-0.971	-0.416

MacKinnon Critical Values for the t-statistics: -2.571 (1%); -1.941 (5%); -1.616 (10%).

Table 4: Unit Roots Tests on Price Series, 1989–90

Table : Field—Level "No Arbitrage Opportunities" Test †

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

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

The number of nodes (N) in each network is the number of pipelines listed. Each model was estimated with three temporal lags (L). The degrees of freedom for the Chi-square test statistic for the exclusion restriction are equal to N(NL+1).

Table 5: No Arbitrage Opportunities Test

continued †

Injection Nodes	Regions	1987-88	1988-89	1989-90	$\chi^2_{.05}$
Network 5					
ANR	Oklahoma				
Northern	Oklahoma				
NGPL	Oklahoma				
Oklahoma	Oklahoma				
Panhandle	Oklahoma	565.09	455.60	N.A.‡	290.02
ANR	North Texas				
Northern	North Texas				
NGPL	North Texas				
PEPL	North Texas				
Network 6					
ANR	Oklahoma				
Northern	Oklahoma				
NGPL	Oklahoma	127.53	99.27	46.11	101.85
Oklahoma	Oklahoma				
Panhandle	Oklahoma				

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

‡ Denotes that model was inestimable due to singularity of the data matrix.

The number of nodes (N) in each network is the number of pipelines listed. Each model was estimated with three temporal lags (L). The degrees of freedom for the Chi-square test statistic for the exclusion restriction are equal to N(NL+1).

The daily spot price data were tested for nonstationarity using the unit root test developed by Dickey and Fuller (1979) along with MacKinnon's (1990) Monte Carlo generated critical values. Because the results of this test are sometimes sensitive to the specification of the testing equation (*e.g.* see Johnston (1989)), the test was run using several different lag lengths. Tables 2, 3, and 4 show the t-statistics from the Dickey-Fuller regressions. The tables also show the precise form and number of lags used in the testing equations. The null hypothesis of a unit root could not be rejected for any of the price series. Furthermore, we performed the same unit root tests on the first differences of the price series and we rejected nonstationarity for each series at the 1% marginal significance level. These test results indicate that each price series is integrated of order one and not greater than one.

The vector autoregression model of equation (7) was estimated for six different network topologies listed in Table 5.[10] Examining the arbitrage opportunities in a variety of network structures over the three subsamples allows us to determine if and how opening the pipeline network led to a convergence in prices across locations and pipelines. We describe the six networks and then discuss the hypothesis testing results.

The first two topologies, listed as Networks 1 and 2, consisted of one node from each of the six 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 (NGPL) and two nodes are on other pipeline systems. Network 2 is more highly connected than Network 1. Estimating the VAR equation for both topologies allows for the possibility that the pressure of arbitrage may not be as high over inter-pipeline networks.[11] Network 3 contains all vertices in the East Texas and Louisiana regions while Network 5 contains all vertices in the Oklahoma and North Texas areas. These networks span large areas and each contains 252 unique arbitrage possibilities. Networks 4 and 6 consist of vertices within a particular region.

Preliminary estimations of the model (eqn. 7) showed that lag lengths longer than three were insignificant, so three lags were used for the estimated models.[12] Table 5 shows the likelihood ratio test statistic for the null hypothesis of 'no unexploited arbitrage opportunities.' For the July 1987–June 1988 subsample, the null hypothesis of a fully arbitraged network can be rejected at the 5% marginal significance level for each of the six network topologies. In the July 1988–June 1989 subsample, the null hypothesis is rejected for all of the networks except Network 6 which consists of the five pipelines in Oklahoma.[13]

[10] We were unable to include all of the nodes in the regression at one time. The number of parameters to be estimated increases quickly as we add nodes to the network.

[11] The additional transactions cost of inter-lining a shipment of gas between pipeline systems should result in a larger set of equilibrium prices.

[12] The qualitative results of the hypothesis tests were not sensitive to the number of lags included in the model. Including three lags ($\mathcal{L} = 3$) in the model ensured that the residual series were serially uncorrelated.

[13] It is interesting to note that for each network, the value of the test statistic decreased between 1987–88 and 1988–89. This is consistent the opening of the pipeline grid even though the hypothesis of no arbitrage opportunities was rejected for five out of six networks.

For the last subsample, 1989–90, the model could not be estimated for Network 5 due to a singularity in the data matrix. The 'no arbitrage' hypothesis was rejected for Network 3, but could not be rejected for any of the remaining networks. By 1989, most pipelines had opened their systems to transportation. The pipeline network appears to have achieved a 'critical' level of connectedness and the results show that gas traders were able to exploit price differences across pipeline networks, whether they were constructed of nodes within or across regions. The results are consistent with the idea that prices will converge as the network becomes more interconnected.

To depict our results graphically, we calculated impulse response functions for Network 1 for each of the subsamples.[14] Using the estimates of the vector autoregression model for Network 1, the following experiment was conducted for each subsample. We exogenously increased the price at an arbitrary node (the impulse) and then traced out the responses of prices at all of the nodes. A simple example will make the computation of the impulse responses more clear: Assume that the impulse is equal to zero for $t < 0$. We then exogenously increase the price on the El Paso Pipeline in West Texas by one unit at $t = 0$ (*i.e.* $\mu_0 = 1$). This increase in price will affect the prices at all nodes in the network at time $t = 1$ through the lagged price variables in the vector autoregression. We trace out the path of prices at each node for $t = 1, 2, \ldots$, assuming that no further exogenous shocks occur. By graphing these impulse responses, we can see the convergence properties of prices in the pipeline network.

However, simulating the path of prices by shocking a single price may be misleading when all of the price series tend to move together. To account for the historical (contemporaneous) correlation in the residuals, they are made orthogonal to one another by use of the Choleski factorization, which is the standard method.[15] These orthogonalized impulses are uncorrelated across equations and across time.

With the impulses orthogonalized as described above, the price at one vertex in the network was increased by a one standard deviation exogenous shock and then the response of each price series was traced through time until convergence was obtained. When the force of arbitrage is strong, non-equilibrium relative prices will be exploited quickly, and prices will converge rapidly to the arbitrage pricing equilibrium. Figures 3, 4 and 5 show the impulse response functions on Network 1 for each subsample: 1987–88, 1988–1989, and 1989–1990. 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 subsample, arbitrage works, but it may take six or seven trading days for prices to converge. In the 1987-1989 subsample, arbitrage is sufficient to dampen prices 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.

[14] See Lütkepohl (1991, pp. 43–59) for a detailed discussion and exposition of impulse response analysis in multivariate time series models.

[15] A drawback of the Choleski factorization is that it differs for each ordering of the variables, so the impulse response functions will also differ; we computed the impulse responses for several orderings of the variables and found that our qualitative conclusions were unaffected. As an alternative to the Choleski factor, the residual covariance matrix could also be factored by an eigen decomposition or a Bernanke-Sims structural decomposition. Theory offered no compelling restrictions to place on the residual covariances, so the structural decomposition method was not pursued.

Impulse Response Functions, July 1987 -- June 1988

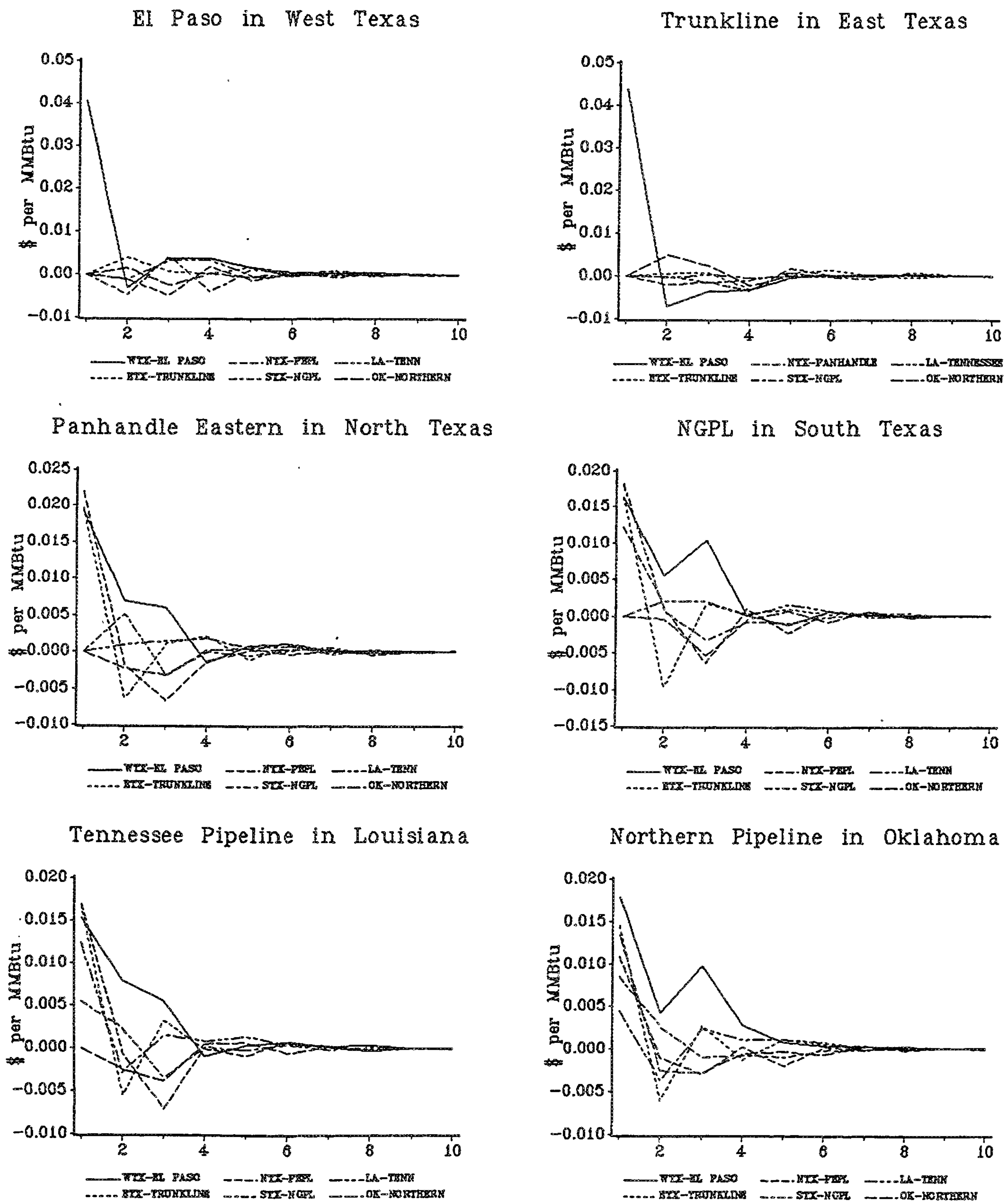


Figure 3: Price Propagation across Network 1, 1987-88

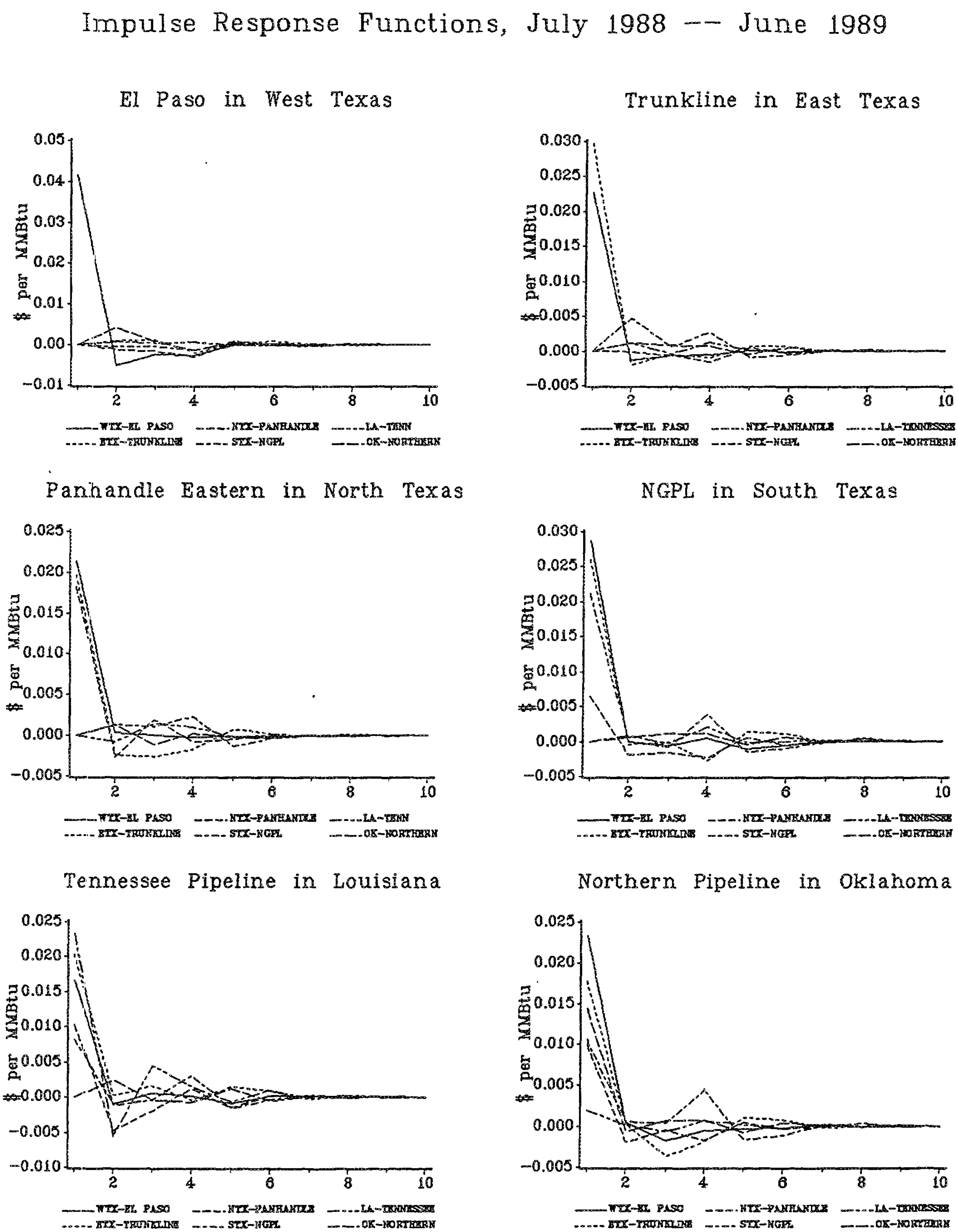


Figure 4: Price Propagation across Network 1, 1988–89

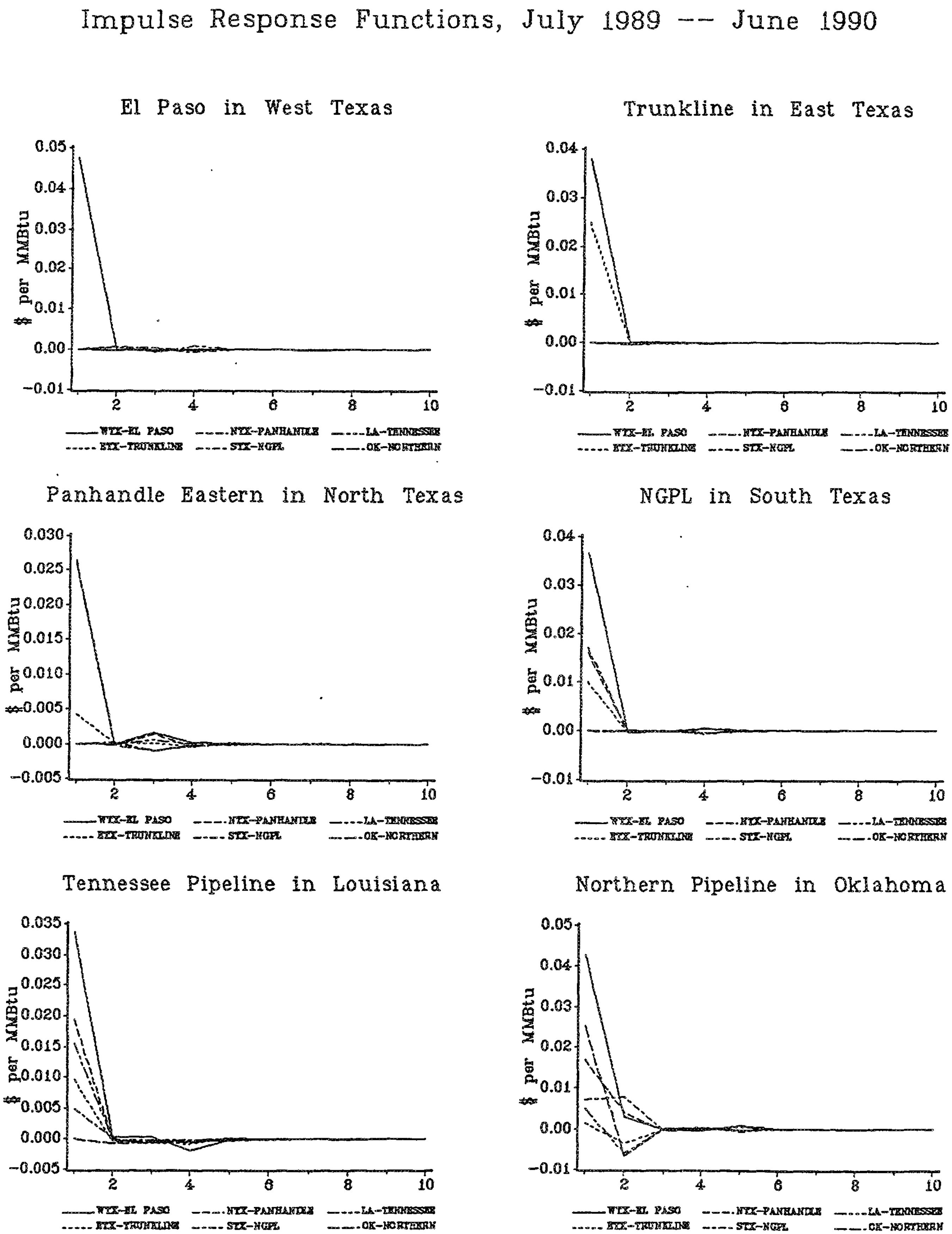


Figure 5: Price Propagation across Network 1, 1989–90

For example, consider the how prices on the Tennessee Pipeline in Louisiana respond to price shocks on other pipelines in Network 1. The top panel of Figure 6 traces out the responses in the 1987–88 sample. It takes about four days for prices to converge. In the lower panel of Figure 6 it can be seen that prices converge rapidly and directly: The impulse is fully absorbed by the second day.[16]

5 Conclusions

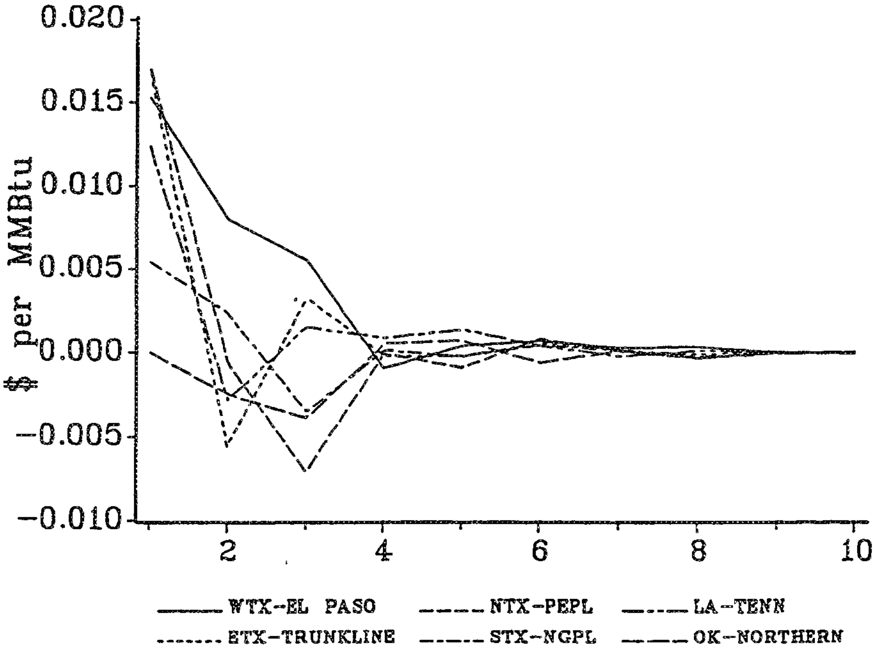
Open access pipeline transportation has had a profound effect on the natural gas industry. Pipelines quickly became transporters rather than sellers of gas and long-term contract sales of gas gave way to spot sales. We have shown that the regulatory system balkanized gas markets by creating a system of individual and protected pipelines that were not interconnected with one another. Open access opened not only individual links in the network, but promoted the emergence of a strongly interconnected network. This transformation of the topology of the pipeline network was a critical factor in promoting convergence of spot prices.

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. The data indicate that the market can absorb sizable 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. The competitive "law of one price" holds over the network and it holds in less than two business days.

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. However, regulation continues to block the full development of markets and competition. In light of the success of competition and markets in disciplining prices—where regulation failed—the lessons of open access should be applied to other markets.

[16] We further estimated confidence bands for the impulse responses to check our results. The impulse responses are highly nonlinear because each price is simultaneously a function of all other prices. This high degree of nonlinearity and the large number of parameters made calculation of confidence bands by the delta method infeasible. As an alternative, we computed confidence bands using a parametric bootstrap suggested by Kloek and Van Dijk (1978). The results showed that the confidence bands during the 1989–90 sample were somewhat shorter than those obtained during the 1987–88 sample. The results are reported in Walls (1992).(Walls, 1992)

Impulse Responses on Tennessee Pipeline in Louisiana: 1987-88



Impulse Responses on Tennessee Pipeline in Louisiana: 1989-90

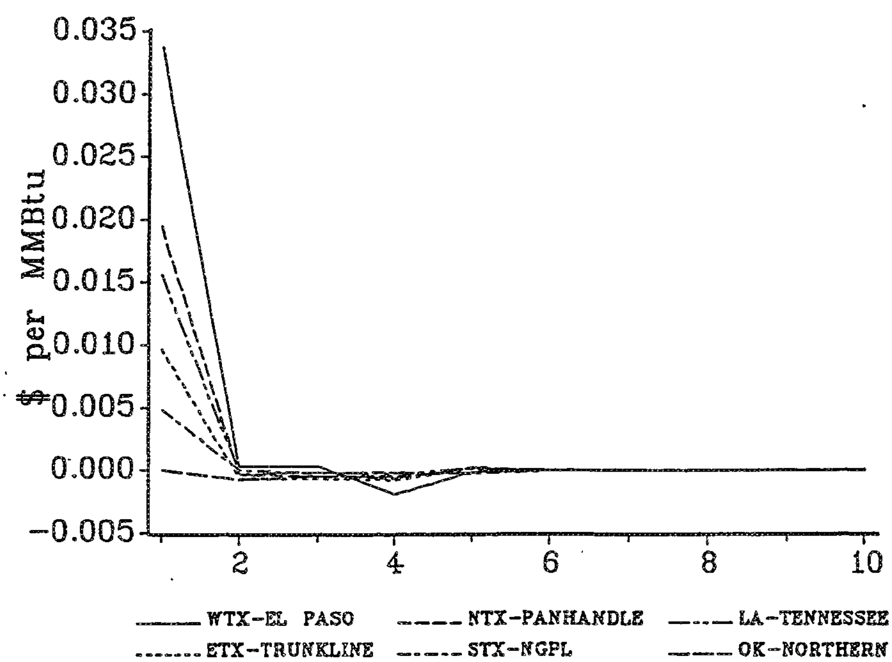


Figure 6: Impulse Responses on the Tennessee Pipeline in Louisiana

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