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ECONOMIES OF SCALE VERSUS TECHNOLOGICAL CHANGE IN THE NATURAL GAS TRANSMISSION INDUSTRY

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Abstract—Although most productivity studies to date assume away scale economies, those studies which both incorporate scale economies and provide a relevant breakdown find that scale economies dominate technological change as a primary determinant of productivity growth. This paper measures the determinants of productivity growth in the U.S. Natural Gas Transmission industry. The technology was estimated using a translog approximation. Results of the econometric model were then utilized to measure the determinants of productivity growth in this industry. It was found that technological change explained certainly as much and often more of productivity growth as did scale economies.

I. Introduction

With some notable exceptions, much of the empirical literature on productivity measurement disregards the potential importance of scale economies. Rather, constant returns to scale are assumed to prevail and technological change is presumed to be the principal determinant of productivity growth.[1] On the other hand, those studies which do incorporate scale economies in their productivity measures find that scale economies explain at least twice as much productivity growth as does technological change.[2] This result, as others have pointed out (e.g., Denny, Fuss and Waverman (1981), p. 206), is rather surprising.

The purpose of this paper is to analyse the components of productivity growth in the U.S. Natural Gas Transmission Industry for the years 1953 to 1979 with a view to determining the relative importance of technological change versus scale economies in generating growth. There are a number of reasons for singling out this industry. First, the technology per se is rather simple. There is only a single output, namely natural gas, which is transported by pipeline over long distances. Second, an upper bound estimate for the scale economy factor, namely 2.07, has been derived from laboratory experiments on pipeline design and used in engineering production function analyses of the gas transmission industry.[3] It is only an upper bound since actual pipeline design is adversely affected, among other things, by terrain and population density factors which are absent in the laboratory.[4] Third, the available data

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[1] See, for example, May and Denny (1979) and Gollop and Jorgenson (1980).

[2] See, for example, Denny, Fuss and Waverman (1981), Nadiri and Schankerman (1981), and Chan and Mountain (1981).

[3] See, for example, Robinson (1972). Previous economic studies which have made use of such laboratory production functions include Callen (1978) and Aivazian and Callen (1981).

[4] Safety requirements, for example, necessitate that pipelines near populated areas have a thicker wall thereby reducing scale economies.

are such that output and inputs to the transmission process can be measured in physical units.[5]

In what follows, section II describes various potentially useful econometric models of the natural gas transmission technology. Section III describes the data. Section IV tests for the premiere model and examines the reasonableness of the parameter estimates. Section V employs this model to estimate the determinants of and their contributions to average labour productivity growth in this industry. Section VI briefly concludes the paper.

II. Econometric Models of the Natural Gas Transmission Technology

As pointed out above, the technology of the natural gas transmission industry is relatively simple. The output, denominated in cubic feet-miles, is generated by compressing the natural gas from the field and sending it through the line-pipe under high pressure until its ultimate destination(s), which is usually a distribution system.[6] The primary inputs to this process are, therefore, the line-pipe, compressor stations, fuel for the compressors (natural gas in the line is used for fuel), and labor. Labor is required to maintain the line, operate and maintain the (non-automatic) compressor stations and fulfill the dispatch function.

Technological change has affected both forms of capital services. Because of technological advances in metallurgy and welding, larger diameter pipes able to withstand greater pressure became practicable and were put into operation. Also, advances in communication and computer technology allowed for the development of semi- and fully-automatic compressor stations which require little or even no manpower to operate.[7]

The early economic studies of pipelines by Chenery (1949), Cookenboo (1952) and more recently Callen (1978), modelled the pipeline production technology by a Cobb-Douglas *engineering* function.[8] These studies abstracted from the issue of technological change. Rather than assuming a Cobb-Douglas form, we will model the technology of natural gas transmission by an *economic* production function of the form

$$Q = F(X_1, X_2, X_3, X_4, T) \tag{1}$$

where Q is the quantity of output measured in cubic feet-miles and X_1, X_2, X_3, and X_4 represent the input quantities of labor, line-pipe capital services, horsepower capital services, and fuel. The time index T measures technical change. We assume that the function F is homogeneous of degree θ in the X inputs so that for any constant c

$$F(X_1, X_2, X_3, X_4, T)\, c^{\theta} = F(cX_1, cX_2, cX_3, cX_4, T). \tag{2}$$

Given the input prices P_i, modified first order conditions which describe the production of Q at minimum cost are[9]

$$S_i = P_i X_i / \sum_{i=1}^{4} P_i X_i = F_i X_i / \sum_{i=1}^{4} F_i X_i = F_i X_i / \theta F = 1/\theta(\partial \ln Q / \partial \ln X_i) \tag{3}$$

where F_i are the partial derivatives of F with respect to X_i. A translog approximation to F along with appropriate substitutions yields

$$\ln Q = \alpha_0 + \tau_T T + 1/2 \tau_{TT} \cdot T^2 + \theta \left(\sum_{i=1}^{4} \alpha_i^* \ln X_i + 1/2 \sum_{i=1}^{4} \sum_{j=1}^{4} \gamma_{ij}^* \ln X_i \ln X_j + \sum_{i=1}^{4} \tau_{iT}^* \ln X_i \cdot T \right) \tag{4}$$

where

$$\sum_{i=1}^{4} \alpha_i^* = 1,$$

$$\sum_{i=1}^{4} \gamma_{ij}^* = 0 \quad \text{for} \quad j = 1 \text{ to } 4,$$

$$\gamma_{ij}^* = \gamma_{ji}^* \quad \forall i, j,$$

$$\sum_{i=1}^{4} \tau_{iT}^* = 0$$

$$S_i = \alpha_i^* + \sum_{j=1}^{4} \gamma_{ij}^* \ln X_j + \tau_{iT}^* \cdot T \quad i = 1,2,3,4. \tag{5}$$

[5] Often, studies in this area are constrained to measure inputs and outputs in (constant) dollars rather than physical units, thereby potentiallly confusing price changes with quantity adjustments. Measuring inputs and outputs in units does not, however, reduce the potential biases resulting from quality changes over time or across companies. In our case, although output quality has remained relatively constant over time, input quality has changed. Thus, newer pipeline companies are likely to experience fewer compressor breakdowns and less line-pipe corrosion. The extent to which these quality differentials affect our results below is unclear.

[6] In addition, there are usually large industrial plants along the line which utilize gas as an input to their productive processes.

[7] Also, advances in compressor technology have reduced fuel consumption. For a description of these and other technological advances, see the *Oil and Gas Pipeline Handbook* (1971).

[8] Given the questions we wish to ask and the available data, our interest lies in estimating an *economic* production function. It can be shown that, in general, the economic production function for gas transmission will not be Cobb-Douglas even if the engineering production function is. We test for and reject the Cobb-Douglas specification further below.

[9] We assume that the industry is a cost minimizer and that input markets are competitive. No assumption need be made about the output market.

We estimate equation (4) plus 3 of the share equations in equation set (5) using industrial panel data from fourteen major interstate natural gas transmission companies.[10] To allow for efficiency differences across firms, we let

$$\alpha_0 = \beta_0 + \sum_{i=1}^{13} \beta_i D_i$$

where

$$D_i = \begin{cases} 1 & \text{for firm } i, \\ 0 & \text{otherwise.} \end{cases}$$

The parameters of the fourth equation can be inferred from the parameter estimates of the other three. The four equations are estimated simultaneously using the full information maximum likelihood procedure.

We consider nine major models in our analysis. These models make alternative assumptions about firm efficiency differentials, technological structure, scale economies (θ) and the rate of technical change ($\partial \ln Q/\partial T$). Specifically, the models under consideration are

Model I: No restrictions on the parameters;
Model II: $\beta_i = 0$ $i = 1,2,\ldots,13$ (no efficiency differentials);
Model III: $\gamma_{ij} = 0$ for all i, j (Cobb-Douglas);
Model IV: $\gamma_{ij} = 0$, $\tau_T = 0$, $\tau_{TT} = 0$, $\tau_{iT} = 0$ for all i, j (Cobb-Douglas and no technological change)
Model V: $\tau_{iT} = 0$ for all i (Hicks neutrality);
Model VI: $\tau_{TT} = 0$;
Model VII: $\tau_T = 0$;
Model VIII: $\tau_T = 0$, $\tau_{TT} = 0$, $\tau_{iT} = 0$ for all i (no technological change);
Model IX: Constant Returns to Scale ($\theta = 1$).

III. The Data

Data were collected on the fourteen major interstate natural gas transmission companies whose financial and operating statistics were reported without interruption in the Federal Power Commission (FPC) Statistics annuals from 1953 to 1979. These data are very detailed and, in fact, separate data are provided for the transmission function of the firm.[11]

Output and input quantities were measured in the following fashion. Output was defined to be the total amount of gas delivered (in cubic feet) to the distribution station multiplied by the length of the line. Horsepower capital services were measured by the total horsepower rating of all the compressor stations along the line. The quantity of line-pipe capital services was measured in terms of tons of steel pipe. The latter was estimated by first multiplying the total length of the line by the square of the average diameter and then multiplying the result by the appropriate proportionality constant.[12] Fuel consumption was specified in terms of cubic feet of natural gas consumed. The quantity of labor applied to transmission services was estimated by calculating the proportion of transmission labor expenses to total labor expenses and multiplying this proportion by the total number of employees in the firm. The price of fuel—and similarly for labor—was estimated by dividing total fuel expense of the year by the quantity of fuel consumed during the period. The price (user cost) of line-pipe and horsepower capital services were obtained in a value-added fashion. Specifically, from total net transmission revenues (net of the cost of gas), the fuel and labor expenses were subtracted. The residual was then allocated between the line-pipe and horsepower inputs on the basis of the ratio of the book value capital cost and operating cost of the line-pipe to the book value capital cost and operating cost of horsepower (i.e., compressors, compressor stations, etc.). After allocating this residual to the capital service inputs, the price of horsepower capital services was computed by dividing its (allocated) residual by the horsepower rating of the line. Similarly, the price of line-pipe capital services was computed by dividing its allocated residual by the quantity (tonnage) of line-pipe.

IV. Estimation

Table 1 provides selected statistics on the nine estimated models described in section II above. In this table, models II to IX are each tested as the null hypothesis against the alternative unrestricted model (model I). The tests involve comparing the evaluated χ^2 statistics—which are obtained from the log likelihood ratios—with the 5% critical values of the χ^2 distribution. As can be seen, all the models were rejected by the data. Thus, we assume model I (the unrestricted model) to be our premiere model.

Table 2 lists the parameter estimates for the unrestricted model. Since $\tau_{PT}^* > 0$ and $\tau_{LT}^* < 0$, this technol-

[10] This particular econometric specification has been previously used by Chan and Mountain (1983, pp. 665–667).

[11] Many of the major interstate pipeline companies have some gas production and distribution facilities as well. Thus, separate data for the transmission function are mandatory.

[12] See Callen (1978, p. 320, equation (A8)). The average diameter is obtained by taking a weighted average of the diameters where the proportions of line-pipe with the specific diameter to the total line-pipe are the weights.

TABLE 1.—SUMMARY OF HYPOTHESIS TESTS

	I	II	III	IV	V	VI	VII	VIII	IX
Log-likelihood statistics	2339.23	2005.68	2135.61	2008.64	2328.03	2335.22	2335.91	2235.40	2206.76
Evaluated χ^2		667.10	407.24	661.18	22.40	8.02	6.64	207.66	264.94
Critical $\chi^2_{.05}$		$\chi^2(13)$ = 22.36	$\chi^2(6)$ = 12.59	$\chi^2(11)$ = 19.68	$\chi^2(3)$ = 7.81	$\chi^2(1)$ = 3.84	$\chi^2(1)$ = 3.84	$\chi^2(5)$ = 11.07	$\chi^2(1)$ = 3.84

TABLE 2.—PARAMETER ESTIMATES OF SELECTED MODEL (MODEL I—UNRESTRICTED)[a]

β_0	1.3107 (0.0854)[b]	β_{12}	−1.8672 (0.0806)	γ^*_{LF}	0.0021 (0.0030)
β_1	−1.0344 (0.0647)	β_{13}	−1.3602 (0.0531)	γ^*_{PP}	0.0778 (0.0103)
β_2	−1.0636 (0.1020)	τ_T	0.0146 (0.0062)	γ^*_{PH}	−0.0165 (0.0066)
β_3	−0.3070 (0.1376)	τ_{TT}	0.0010 (0.0004)	γ^*_{PF}	−0.0563 (0.0050)
β_4	−1.3841 (0.0535)	θ	1.9223 (0.0552)	τ^*_{HH}	0.0440 (0.0064)
β_5	−1.5307 (0.0689)	α^*_L	0.1142 (0.0088)	γ^*_{HF}	−0.0015 (0.0046)
β_6	−1.3671 (0.0737)	α^*_P	0.5890 (0.0088)	γ^*_{FF}	0.0557 (0.0065)
β_7	−1.5838 (0.0638)	α^*_H	0.2047 (0.0076)	τ^*_{LT}	−0.0011 (0.0002)
β_8	−1.0316 (0.0684)	α^*_F	0.0921 (0.0048)	τ^*_{PT}	0.0010 (0.0005)
β_9	−1.4372 (0.0923)	γ^*_{LL}	0.0289 (0.0046)	τ^*_{HT}	0.0001 (0.0004)
β_{10}	−1.5128 (0.0670)	γ^*_{LP}	−0.0050 (0.0049)	τ^*_{FT}	0.0000 (0.0002)
β_{11}	−1.3049 (0.0799)	γ^*_{LH}	−0.0260 (0.0053)		

Log Likelihood Function 2339.23

[a] The subscripts T, L, P, H and F are assigned to coefficients associated with time, labor, line-pipe capital services, horsepower capital services, and fuel.

[b] Standard errors are in parentheses.

ogy is line-pipe using and labor saving.[13] This corresponds to our intuition. Technological change in the industry definitely increased the usage of larger diameter line-pipe. Also, advances in compressor technology reduced the need for manpower in running these stations as fully manned stations either became semi-automatic or completely automatic over time. τ^*_{HT}, τ^*_{FT} are not significantly different from zero. This is not all that surprising. On the one hand, compressors became more fuel efficient (per unit of rated horsepower) and more powerful over time. On the other hand, secular growth in output required more compressors and these tended to be larger than the ratings of the earlier capital stock.

A more important parameter estimate of interest to this study is that of scale economies $\hat{\theta} = 1.92$. The t-statistic for $\hat{\theta}$ as distinct from 1 is 16.7083. As expected for the pipeline industry, not only does $\hat{\theta}$ show significant increasing returns to scale but $\hat{\theta}$ is also less than 2.07, the aforementioned upper limit laboratory value for θ.

V. The Component of Productivity Growth

Having estimated the technology for gas transmission, we are now in a position to estimate the components of productivity growth in this industry. A common measure of productivity is the change in the Average Productivity of Labor ($\dot{APL}$). As shown by Chan and Mountain (1981), $\dot{APL}$ can be decomposed into three basic components: shifts into factors of production other than labor, technological change as measured by a modified (for scale economies) Tornqvist index of Total Factor Productivity, and a returns to scale factor. Specifically, if we relabel the inputs $X_1 = X_L$, $X_2 = X_P$, $X_3 = X_H$ and $X_4 = X_F$ (L stands for

[13] The τ_{iT}^* indicate where the share of input i has decreased or increased due to technological change. See Sato (1965).

TABLE 3.—WEIGHTED GROWTH RATES OF CONTRIBUTING FACTORS TO AVERAGE LABOR PRODUCTIVITY

Firm	Pipeline Capital Deepening $S_P(\dot{X}_P - \dot{X}_L)$	Horsepower Capital Deepening $S_H(\dot{X}_H - \dot{X}_L)$	Fuel Deepening $S_F(\dot{X}_F - \dot{X}_L)$	Rate of Technological Change $T\dot{F}P$	Returns to Scale $(\theta - 1)(S_L \dot{X}_L + S_P \dot{X}_P + S_H \dot{X}_H + S_F \dot{X}_F)$	Average Labor Productivity $A\dot{P}L$
Cities Service	1.18	0.43	0.22	1.47	1.43	4.80
Gas Company	(24.94)	(9.12)	(4.64)	(31.08)	(30.22)	(100.00)
El Paso Natural	−2.11	−0.16	0.27	2.73	1.09	1.77
Gas Company	(−121.67)	(−9.40)	(15.60)	(153.62)	(61.8)	(100.0)
Michigan Gas	3.23	1.52	0.08	0.27	1.58	6.83
Storage Company	(48.16)	(22.82)	(1.28)	(4.01)	(23.74)	(100.00)
Michigan Wisconsin	0.80	0.21	−0.06	4.51	5.89	11.73
Pipe Line Company	(7.23)	(1.92)	(−0.52)	(39.80)	(51.58)	(100.00)
Natural Gas Pipeline	1.90	0.82	0.17	4.71	5.28	13.44
Company of America	(14.91)	(6.50)	(1.32)	(36.48)	(40.79)	(100.00)
Northern Natural	−0.13	2.37	0.38	6.47	3.41	12.98
Gas Company	(−1.07)	(19.16)	(3.14)	(51.33)	(27.44)	(100.00)
Panhandle Eastern	0.15	0.50	0.20	3.71	2.12	6.82
Pipe Line Company	(2.33)	(7.53)	(3.06)	(55.23)	(31.85)	(100.00)
Southern Natural	0.83	0.29	0.11	3.35	2.70	7.44
Gas Company	(11.45)	(4.10)	(1.47)	(45.83)	(37.14)	(100.00)
Tenneco Inc.	1.42	0.90	0.21	4.68	2.12	9.61
	(15.40)	(9.72)	(2.25)	(49.81)	(22.82)	(100.00)
Texas Eastern	0.31	0.49	0.21	1.13	2.81	5.02
Transmission Company	(6.26)	(9.91)	(4.26)	(22.97)	(56.60)	(100.00)
Texas Gas Trans-	1.91	0.78	0.27	2.64	3.18	9.05
mission Corporation	(21.81)	(8.97)	(3.10)	(30.02)	(36.10)	(100.00)
Transcontinental	1.78	0.27	−0.08	4.17	4.64	11.17
Gas Pipeline Corp.	(16.69)	(2.56)	(−0.72)	(38.59)	(42.88)	(100.00)
Trunkline Gas	0.32	0.79	0.27	4.47	5.32	11.55
Company	(2.92)	(7.16)	(2.48)	(40.02)	(47.42)	(100.00)
United Gas Pipeline	−0.35	0.07	−0.04	2.30	−0.37	1.59
Line Company	(−22.07)	(4.19)	(−2.63)	(143.68)	(−23.18)	(100.00)

labor, P for line-pipe, H for horsepower capital and F for fuel),

$$A\dot{P}L = \dot{Q} - \dot{X}_L = S_P(\dot{X}_P - \dot{X}_L) + S_H(\dot{X}_H - \dot{X}_L) + S_F(\dot{X}_F - \dot{X}_L) + T\dot{F}P + (\theta - 1)(S_L \dot{X}_L + S_P \dot{X}_P + S_H \dot{X}_H + S_F \dot{X}_F) \tag{6}$$

where the S's denote cost shares, dots above the variables denote discrete logarithmic changes (e.g., $\dot{Q} = \ln(Q_t/Q_{t-1})$), and $T\dot{F}P$ denotes changes in total factor productivity. The first three terms on the right hand side of equation (6) are the shifts into alternative factors of production; the fourth term is a measure of technological change; the last term is a scale economy factor.

Table 3 gives the decomposition of $A\dot{P}L$. An examination of the first three terms reveals that most of the shift from labor is into line-pipe capital, then horsepower capital and to a lesser extent fuel. More importantly, for most firms, over 60% of the growth in average labor productivity is due to the combination of technological change and returns to scale. However, what is most interesting is the breakdown between these latter two components. Unlike previous research which found that scale economies explained at least twice as much of productivity growth as did technological change, in the case of the natural gas transmission industry technological change was at least as important as scale economies. Over the fourteen companies, the average percentage contribution of returns to scale was 34.80% and technological change was 53.03%.

VI. Conclusion

Although most productivity studies to date assume away scale economies, these studies which both incorporate scale economies and provide a relevant breakdown find that scale economies dominate technological change as a primary determinant of productivity growth. This finding is surprising.

The purpose of this paper has been to measure the determinants of productivity growth in the U.S. Natural Gas Transmission industry from 1953–1979. This industry was chosen because the technology is rather simple, there is a single output and the input-output data are available in physical units. It was found that on the whole, the parameter estimates of the technology correspond to our a priori expectations. The results of the econometric model were then utilized to measure the determinants of productivity growth in this industry. Contrary to what was found for other industries, technological change explained certainly as much and often more of productivity growth than did economies of scale. Of course, it may be that this result is unique to the natural gas transmission industry. This could be due to the simplicity of the industry or the ability to easily isolate and physically measure the inputs and outputs. Nevertheless, the topic is sufficiently important that it calls for additional research to resolve this issue in other industries.

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STUDENT GENDER AND SCHOOL DISTRICT DIFFERENCES AFFECTING THE STOCK AND FLOW OF ECONOMIC KNOWLEDGE

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Abstract—A large data set of over 3,000 students from more than 75 Indiana public school districts is analyzed to determine whether male students in four different grade levels exhibit significant advantages in levels of economic understanding or learning over the course of a school year. Males were found to have higher levels of economic understanding as early as grade 5, and learned significantly more than females in some grades where no formal economics instruction was provided. Formal instruction appears to reduce these differences somewhat, and in some districts the differences are eliminated even before such instruction is given.

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A number of recent studies, including two in this *Review* (Buckles and Freeman, 1983; Siegfried and Strand, 1977), have tried to establish under what circumstances males score higher than females on standardized tests of economic understanding. There are several reasons, many of which are controversial, offered to explain why these differences exist in those cases where they are observed: different socialization processes may direct males to, and females away from, the study of material that is often quantitative and business ori-