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Natural Monopoly in Canadian Interprovincial Gas Pipelines

by

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Abstract

This thesis provides a review of natural monopoly theory, the theory of the firm from a cost perspective in a multiple output environment, and an econometric application of this theory to interprovincial natural gas pipelines in Canada.

We investigate single and multiple output cost function properties in output space as well as the necessary and sufficient for natural monopoly (subadditivity) in both cases. We then estimate several trans-log cost functions with data collected regarding TransCanada Pipelines and test these functions for indirect and direct evidence of subadditivity.

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Thank you very much indeed.

Dedication

This work is dedicated to Henrietta Pawluk, who after suffering a major stroke still inspires those who know her to be the best that they can be.

TO MOM.

Table of Contents

List of Tables

List of Figures

List of Symbols

Unless otherwise noted in the text, the following conventions will be used throughout this thesis.

C	implies a cost function.
S	implies economies of scale.
f	implies a single output production function.
ϕ	implies a multiple output production function.
y and Y	imply output.
Any single subscript	implies first order partial derivative of a function with respect to the variable denoted by the subscript, except when the subscript is on y or Y. In this case, the subscript implies specific outputs only.
Any double subscript	implies second order partial dderivative of a function with respect to the variables denoted by the subscripts.
g or G	imply the price of natural gas.
i or I	imply the interest rate.
w or W	imply the wage rate unless presented in brackets with y, for example C(y,w), in this case w implies all prices.

CHAPTER ONE: INTRODUCTION

1.0 Introduction

The break up of the Bell telephone system in the United States has attracted some attention in the natural monopoly literature[1]. This research has attempted to determine which market structure would result in the provision of telephone services at the lowest cost to the paying public. That is, is there a cost savings to having only one firm provide telephone services through a single network, or through several firms and several telephone networks? Such research[2] was influential in the decision to break-up the Bell system.

Historically, economists have looked toward economies of scale as a measure for determining the natural monopoly status of a particular industry. Some economists have argued that if increasing returns to scale exist, and there are multiple firms serving a market, each firm will not be producing enough output to take advantage of increasing returns to scale. In this case, industry costs would be minimized only if a single firm, a monopolist, supplies the entire market (Berg and Tschirhart, 1988, p. 21).

Note that if industry costs are minimized only when a single firm supplies the entire market, such a firm is called a natural monopolist. Further note that the literature in this field has attempted to determine whether or not

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1 For example see Roller (1992), Shin and Ying (1992) and Shepherd (1990, pp. 409 - 414). For a list of books written on the Bell system divesture see Shepherd (1990, p. 409).

2 The study performed by Evans (1983).

a certain monopoly is one which occurs naturally or has been brought into existence by some mechanism other than the market[1].

Given the potential importance of such research on network technology driven natural monopolies[2], it is surprising that relatively little attention has been paid to this topic with regard to pipelines. This is especially so in Canada where a single firm, Trans-Canada Pipelines Ltd. (TCPL), is responsible for shipping natural gas through a network of pipelines across Canada and into the United States.

This thesis proposes to fill this gap in the literature by presenting natural monopoly theory with an econometric application studying TCPL's transmission system. Particularly, this study proposes to discover what industry configuration yields the lowest cost of transportation of natural gas in Canada. However, a little background information on TCPL is in order before we continue.

1.1 Background on TCPL

TCPL is currently regulated under the National Energy Board Act (1959, c.46, s.1.), which gives the National Energy Board of Canada (NEB) jurisdiction to make rulings with respect to TCPL's tolls, expansions, and

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1 For example, by regulation or barriers which hamper free entry into the market.

2 Such research could result in considerable cost savings being realized in the natural gas transportation market, and like the Bell system, such research could dramatically change the structure of the natural gas transportation market in Canada.

allowed rate of return. Under this act, the NEB also has the authority to grant a certificate without which no pipeline in Canada may transport natural gas (NEB Act. 1959, c. 46, s.26). The procedure of granting certificates effectively gives TCPL a monopoly status in the transportation of natural gas from the Empress site in southern Alberta to points in Ontario and certain delivery points in the United States.

Since TCPL's mainline started to deliver gas in 1958 (Annual Reports, 1985, p. 5), TCPL has undergone several changes. Until 1986 TCPL had authorization to engage in the selling as well as the transportation of natural gas. On October 31, 1985, the Western Accord was signed by the governments of Canada, Alberta, British Columbia and Saskatchewan (Annual Reports, 1985, p.12). This accord changed the procedure of pricing natural gas. As a result of this accord, the price of natural gas in Canada was allowed to fluctuate according to market conditions, rather than being wholly regulated by the NEB as had been done previously. Shortly after this accord was signed, TCPL created a separate company, Western Gas Marketing, "responsible for the administration of TransCanada's gas purchase and sale contracts, and for expanding markets for western Canadian natural gas (Annual Reports, 1985, p.14)." Additionally, TCPL has undergone several expansions since 1958, continuously adding to its mainline while obtaining interests in other pipelines and petroleum related industries on a global scale. Currently TCPL is divided into two divisions. The first division is a general division dedicated to petroleum related concerns which include a liquid petroleum gas extraction plant at the Empress site in Alberta[1], electrical generation plants in Ontario and other global interests[2]. The second division, the one of concern in this thesis is the regulated division which is solely responsible for the transportation of natural gas across Canada and for export into the United States. This division currently operates a natural gas transmission system (pipeline network) consisting of a mainline system comprising 13,687 kilometres of pipe, 1,627 megawatts of compression, 56 compressor stations and 200 meter stations (Annual Reports, 1993, p. 6). In addition, deliveries of natural gas have recently increased substantially, more than doubling in the past 5 years. This increase in demand has come primarily from municipalities in Eastern Canada and from several large industrial users of natural gas in both Canada and the United States. Deliveries are currently in the region of 55.82 Billion cubic meters (Bcm)[3] per year. Of this volume, 32.17[4] Bcm per year are delivered domestically while 23.65[5] Bcm per year are exported (Annual Report, 1992, p. 10).

In addition to this information, it is important to note that under the National Energy Board Act, the NEB has the authority to regulate TCPL's activities, and in particular, TCPL's tariffs and delivery volumes (NEB Act,

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1 Several petroleum products are extracted from the raw natural gas at this site. These products include propane, butane, and ethane (a primary component in the commercial production of plastics).

2 A complete listing of TCPL's subsidiary and investment interests is included in Appendix 1.

3 1.971 trillion cubic feet (tcf).

4 1.14 tcf.

5 0.835 tcf.

1959, c. 46, s. 55 and s. 60). TCPL's tariff is set at regularly held hearings, while delivery volumes are usually at the discretion of TCPL, operating as a contract carrier[1].

1.2 Purpose of Study

The purpose of this study is two-fold. First, to econometrically estimate the long-run cost function for TCPL. This will provide information on economies of scale and other cost curve characteristics. Second, to use this information to determine if an alternative market structure[2] could result in lower cost of service to the entire market. This study proposes to answer the question: "What is the market structure which would result in the transportation of natural gas at the lowest cost in Canada?" The answer to this question could result in either justification for the break up of TCPL, or justification for allowing TCPL to continue serving its customers as a monopolist.

The body of this thesis will progress in the following order: Chapter two contains a discussion and development of natural monopoly theory and its application to TCPL's natural gas pipeline. Chapter three presents problems with econometric application of the theoretical concepts discussed in Chapter two. Chapter four contains a short discussion of previous applied work in this field, and Chapter five contains the econometric estimation of several

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1 TCPL requires a delivery contract with all of its customers, and as such is commonly referred to as a contract carrier.

2 For example, two firms supplying the gas transportation market instead of only one firm.

cost functions for TCPL, tests for natural monopoly, interpretation of test results, and the conclusion to this thesis.

CHAPTER TWO: NATURAL MONOPOLY THEORY

2.0 Introduction:

In this chapter, I discuss the theory of natural monopoly concentrating on the necessary and sufficient conditions for a natural monopoly to exist. I begin with a few definitions of relevant concepts and then discuss the sufficient conditions for natural monopoly to exist. Following this, I discuss the necessary conditions for natural monopoly, and the possibility of TCPL being a natural monopoly in light of these necessary and sufficient conditions.

2.0.1 Subadditivity

A natural monopoly is one which can supply the entire market at lower cost than two (or more) firms. This cost property has been called subadditivity[1]. A cost function is globally subadditive if (Berg and Tschirhart, 1988, p. 23):

$$C(Y) < \Sigma C(y_i)$$

$$\text{Subject to:} \quad Y = \Sigma y_i$$

Where: C represents the cost function.

Y is the output of the monopolist.

y_i is the output of each firm (assuming there is more than one) in the industry.

This equation states that no combination of smaller firms can collectively

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1 Simply put, if the cost function is globally subadditive then industry costs are minimized only when a single firm is supplying the entire market.

produce industry output at a lower cost than a monopolist[1]. Hence, if the cost function exhibits subadditivity then a single firm results in the minimization of industry costs, and the industry is a natural monopoly.

A cost function may also exhibit properties other than subadditivity. A cost function may exhibit additivity, or superadditivity in addition to subadditivity. When the above inequality is reversed (replaced with an equality sign), the cost function is said to exhibit superadditivity (additivity). In the case when the cost function displays additivity, there are no additional costs, or cost savings, to be realized if the monopolist is split up into two smaller firms. Meanwhile, if a cost function shows superadditivity, two firms can supply the market at lower cost than one firm. Notice that the existence of superadditivity gives evidence to disprove the existence of a natural monopoly (Berg and Tschirhart, 1988, p. 23).

The most interesting circumstance is when the cost function exhibits regions of superadditivity, subadditivity and additivity. In this case, a natural monopoly may still exist if the cost function exhibits subadditivity in the relevant region. That is, with regard to policy decisions, it may be the case that the monopolist industry configuration provides production at the least cost. In this case, the monopolist in question would be a natural one, but only when it produces in the region where the cost function features subadditivity. The important questions now are: Where does subadditivity

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1 The hypothetical firms may split up the monopolists output between themselves according to any number of algorithms. We have assumed implicitly that these hypothetical firms play a Bertrand game and thus that they split market share evenly between themselves.

come from, and what features are responsible for it? Section 2.1 contains the answers to these questions, but first, two more relevant concepts must be introduced.

2.0.2 Economies of Scale

Economies of scale[1] can be presented in either a cost function or a production function framework. In a production function framework, economies of scale occur when a firm halves its inputs, the firm more than halves its outputs. This can be shown by the following formula:

$$f(tx) < tf(x), \quad for\ all \quad 0 < t < 1$$

Where: f is the production function.

x is the vector of inputs into the production process.

t is a scaling factor.

This equation says that if inputs are decreased by a certain factor, then output decreases by a larger factor. This implies that if inputs are increased by a certain factor then outputs will increase by a greater factor. This phenomenon can also be represented with the cost function. The mathematical development of economies of scale from the cost function is presented below.

From microeconomic theory[2]; minimization of the firms cost, subject to

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1 For this thesis, economies of scale should be interpreted as strictly increasing returns to scale. Similarly, diseconomies of scale should be interpreted as strictly decreasing returns to scale.

2 F(x) - y implies that y is a scalar measure of output. Here it is convenient to use the notation $\phi(x,y)$, a more general notation which (continued...)

the constraint that production attain some non-zero level,

$$C(y,w) = \min\ [wx,\ such\ that\ x \geq 0,\ \phi(x,y) \geq 0],$$

yields the following Kuhn-Tucker conditions:

$$(1.1) \quad w_i - \lambda \frac{\partial \phi(x,y)}{\partial x_i} \geq 0$$

$$(1.2) \quad x_i^* \left\{ w_i - \lambda \frac{\partial \phi(x,y)}{\partial x_i} \right\} = 0$$

$$(1.3) \quad \phi(x^*,y) \geq 0, \quad \lambda \geq 0, \quad \lambda \phi(x^*,y) = 0$$

Now, if we sum (1.2) over all x_i and note that after the firms cost is minimized it may be represented as the sum of input prices times the factor demand equations[1], x^*,

$$C(y,w) = wx^*(y,w),$$

which can be rewritten as;

$$(1.4) \qquad C(y,w) = \lambda \sum x_i^* \frac{\partial \phi(x,y)}{\partial x_i}$$

The optimized Lagrangian for this problem is then given by:

$$C(y,w) = wx^* - \lambda \phi(x^*,y)$$

and applying the Envelope theorem, we obtain:

$$(1.5) \qquad C_j = -\lambda \frac{\partial \phi(x^*,y)}{\partial y_j}$$

2(...continued)
allows y to be a vector of several different outputs, without affecting the derivation.

1 These are obtained by applying Shephard's Lemma to the cost function. These demand equations tell us the level of each input which the firm will demand for each level of output that the firm wishes to produce, at market prices.

Now, if we divide equation (1.4) by equation (1.5) we obtain:

$$S(y,w) = -\frac{\left[\lambda \sum x_i^* \frac{\partial \phi(x,y)}{\partial x^*}\right]}{\left[\lambda \sum y_j \frac{\partial \phi(x,y)}{\partial y_j}\right]} = \frac{C(y,w)}{\sum y_j C_j(y,w)}$$

Where S(y,w) is Panzar's (1989) measure of multiproduct scale economies.

In the single output case, this reduces to a form which has a familiar economic interpretation. S(y,w) reduces to:

$$S(y,w) = \frac{C(y,w)}{yC_y} = \frac{C(y,w)}{y} * \frac{1}{C_y} = \frac{AC}{MC}$$

Where AC and MC are average and marginal costs respecively.

which implies that returns to scale are increasing when AC > MC (S > 1), constant when AC = MC (S = 1), and are decreasing when AC < MC (S < 1).

Unfortunately, in the multiple output case, this analogy is not applicable because average cost is not a clearly defined concept. To get around the problem, S(y,w) "...relates total cost (in the numerator) to attributable costs[1] in the denominator (Waterson, 1988, p.20)." We can interpret S(y,w) in this case as saying: if scale economies are present, and we look along a ray from the origin, average costs along that ray are falling.

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1 These are costs which are attributable to the production of each output, summed over all outputs. This is derived by multiplying the quantity of each output by the product specific marginal costs of that output, and summing over all outputs. Alternatively, this may be viewed as the sum of output-weighted marginal costs.

Hence output-weighted marginal costs are below total cost so that S > 1. Conversely, if diseconomies of scale are present S < 1, and if there are constant returns to scale, S = 1.

This analysis yields the insight that there are two approaches for determining scale economies. We could determine which part of the average cost function the firm is producing in (in the single output case), or, in the multiproduct case, estimate degrees of scale economies from the cost function.

2.0.3 Economies of Scope:

The last concept to be introduced in this section is economies of scope. Economies of scope are said to be present if there are cost savings when several products are produced jointly instead of separately. Following Panzar (1989, p. 16), in the two product case, this can be shown as:

$$C(y_1,y_2) < C(y_1,0) + C(0,y_2)$$

where y_1 and y_2 are different products. Here the cost associated with producing products y_1 and y_2 by a joint production process are strictly lower than the costs associated with producing these products separately[1].

Now let us consider the circumstances responsible for this phenomenon. Economies of scope arise from two sources, weak cost complementarities and fixed costs. I discuss each of these in turn.

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1 Note that economies of scope is merely a special case of subadditivity, where the monopolists output is partitioned between two hypothetical firms in a special way. Each hypothetical firm is permitted to specialize in one of the outputs of the monopolist.

Weak cost complementarities are said to exist if the marginal cost of producing one product decreases when the output of another jointly produced product increases (Squires, 1988, p. 362).

Mathematically, cost complementarities can be shown as:

$$C_{12} = \frac{\partial C^2}{\partial y_1 \partial y_2} < 0; \; y_1 \neq y_2, \; \textit{for all } y_1, y_2 > 0$$

$$C_{12} = \frac{\partial C^2}{\partial y_1 \partial y_2} \leq 0; \; y_1 \neq y_2, \; \textit{for all } y_1, y_2 \geq 0$$

where y_1 and y_2 are individual products. Notice that if $C_{12} < 0$, then joint production of a certain quantity of each product is strictly less expensive than separate production, that is, if cost complementarities exist then so do economies of scope.

An example of cost complementarities is easy to imagine. Consider the joint production of beef and leather. Suppose that a farmer is engaged in the production of both beef and hides. Suppose further that the farmer is currently producing 10 hides and 10 carcasses. At this level of production, the marginal cost of hide production is some positive amount. Suppose that the farmer now increases carcass production by one unit. The marginal cost of producing another hide has dropped dramatically as the hide is a natural by-product of the increased carcass production. The marginal cost of producing one product has decreased when the output of another jointly produced product has increased.

In the absence of weak cost complementarities, large common costs may be sufficient for economies of scope to exist. In this case, large common costs in the form of plant and equipment may be shared between the production of two or more products. Even though cost complementarities may not exist, joint production involving the sharing of large common costs may result in a cost advantage over separate production.

2.1 Necessary and Sufficient Conditions for "Natural" Monopoly

As the definition of natural monopoly is that the cost function exhibits subadditivity, it is important to consider which conditions are necessary and/or sufficient for subadditivity. Global subadditivity exists only when local subadditivity exists for all possible divisions of the monopolists output. Hence, the important question, and the one which focuses our attention, is: "What are the necessary and sufficient conditions for global subadditivity?" In this section I introduce, develop and discuss these conditions.

Interestingly, the necessary and sufficient conditions for a natural monopoly change when we move from a single output to a multiple output monopolist. For this reason, we must discuss the necessary and sufficient conditions under each case separately. I begin with the single output case and then move to the multiple output case.

2.1.1 Single Output Monopolist

In the single output case, economies of scale are a sufficient, but not a necessary condition for global subadditivity. To show this, I begin with a diagrammatic example to argue that economies of scale are not a necessary condition for subadditivity. I then present a mathematical proof of the sufficeincy and non-necessity of this condition for subadditivity to exist.

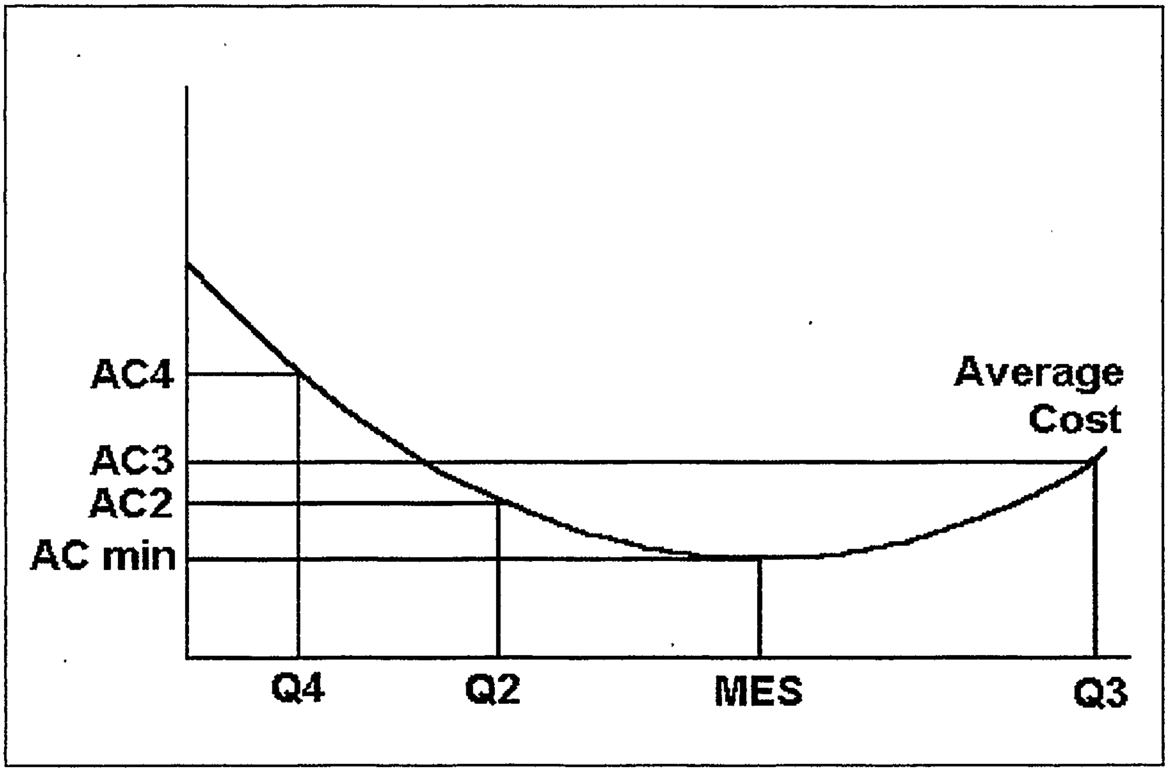

Figure 1.1

In order to see that economies of scale are not a necessary condition for subadditivity, consider Figure 1.1. Figure 1.1 shows the average cost function of a single output monopolist. Notice that this average cost function has an upward sloping part and recall that in the single output case that economies of scale exist only in the downward sloping portion of the average cost function. The monopolists average costs of production are minimized at

AC min and MES, the minimum efficient scale. Suppose that the market demands Q3 units of output. If the monopolist produces this level of output it incurs average costs AC3. Now suppose that two identical sized firms are supplying this market, producing Q2 each while supplying the entire market (producing Q3). Here, each firm incurs average cost AC2 and as a result the industry structure which minimizes industry cost is the two firm structure. In this case it makes no sense to have a single firm supplying the market when two firms can do so at lower cost. Alternatively, consider the case when the two identical sized firms would have to produce Q4 each in order to supply the entire market. The hypothetical firms would incur average costs of AC4 under these circumstances. If this is the case, the monopolist could supply the entire market at the lowest cost. In general, if the monopolist is operating in the upward sloping portion of the average cost function, it may or may not be the case that two smaller firms can supply this market at lower cost. Further, this implies that increasing returns to scale are not a necessary condition for global subadditivity (a natural monopoly) to exist.

I now present a formal proof of this. This demonstration has the following organization: First, I introduce a cost function which exhibits regions of subadditivity, additivity and superadditivity. Then I show that this cost function continues to exhibit subadditivity even in a production region where average cost is rising.

Assume the monopolists' cost function can be represented as[1]:

$$C(y) = F + a\,y^2$$

1 Following Panzar (1989, p.10).

Where: y is the monopolists' output.

F is fixed production cost.

Now, it is convenient that global subadditivity may be represented as:

$$C(y) < KC\left(\frac{y}{K}\right)$$

$$\text{for any} \quad K \subset \{\mathbb{I} > 1\}$$

Here, K is an integer constant greater than one. This number represents the number of smaller firms which will replace the monopolist. Note that it is assumed implicitly that these firms will split market share evenly among themselves. This need not happen, but this restriction greatly simplifies the following proof. Now, this cost function is subadditive if:

$$F + ay^2 < KF + Ka\left(y/K\right)^2$$

Substituting an equals sign for the less than sign, and solving for y yields:

$$y = \sqrt{(KF)/a}$$

which allows us to determine the exact region where this cost function exhibits subadditivity, additivity and superadditivity. In particular, this cost function is subadditive through $0 < y < \sqrt{(KF)/a}$, is additive if $y = \sqrt{(KF)/a}$, and is superadditive if $y > \sqrt{(KF)/a}$.

We now turn our attention to the monopolists average cost function:

$$AC = \frac{F}{y} + ay$$

If we set the first partial derivative of the average cost function to zero,

$$\frac{\partial AC}{\partial y} = -\frac{F}{y^2} + a = 0,$$

this allows us to find the minimum efficient scale of operation (MES). Recall that average cost is falling at lower production levels than MES, minimized at MES and rising above MES. Solving the above equation for y yields the answer that average cost is minimized at:

$$y = \sqrt{F/a}$$

It now follows that, as K > 1:

$$\sqrt{(KF)/a} > \sqrt{F/a}$$

Which states that the point where subadditivity is exhausted exceeds the minimum efficient scale of production in this industry. Thus C(y) is subadditive even in a region where average cost is rising. Decreasing average cost is not a necessary condition for global subadditivity, and therefore economies of scale are also not a necessary condition for global subadditivity.

We now turn our attention to the sufficiency of economies of scale for subadditivity. This proof follows the logic that if decreasing average cost is sufficient for subadditivity then so are economies of scale. The following development is from Berg and Tschirhart (1988, p.23).

Decreasing average cost can be shown mathematically as:

$$\frac{C(y^i)}{y^i} > \frac{C(y)}{y}$$

Subject to: $0 < y^i < y$

Where y ≤ MES

This expresses the idea that average cost is greater for any y' less than y, a concept which implies decreasing average cost up to y. After manipulating this equation, we can obtain:

$$C(y^i) > \frac{y^i}{y} C(y)$$

Now, if we sum both sides over all i we obtain:

$$\Sigma C(y^i) > \frac{\Sigma y^i}{y} C(y)$$

If $\Sigma(y^i)/y = 1$ (the output from all hypothetical firms equals the output of the monopolist), this can be written as: $\Sigma C(y^i) > C(y)$, which is the definition of global subadditivity. Decreasing average cost implies subadditivity, and is therefore a sufficient condition for subadditivity to exist. As decreasing average cost implies economies of scale, it then follows that economies of scale is also a sufficient condition for subadditivity.

In the case of the single output monopolist, economies of scale forms a sufficient but not necessary condition for subadditivity to exist. If the monopolists' average costs of production are decreasing it is not possible for any combination of smaller firms to produce at lower industry costs, and hence economies of scale forms a sufficient condition for subadditivity. However, economies of scale is not a necessary condition as it may not be possible for any combination of smaller firms to produce at lower industry costs even if the monopolist is operating in a region where average cost is increasing.

2.1.2 Multiple Output Case

We now turn our attention to the multiple output monopolist, and the necessary and sufficient conditions for subadditivity. Unfortunately, the single product firm results are not applicable when more than one output is produced. Indeed, in order to find necessary and sufficient conditions for subadditivity, several new economic concepts are developed. The results show that no single condition can be found to be necessary and sufficient for subadditivity in the multiple output case. However, conditions are found which are sufficient for subadditivity, and one condition is found to be necessary.

The following discussion will yield two important properties of the cost surface, which combined will yield a sufficient condition for subadditivity. These two properties are declining ray average costs and transray convexity (Baumol, Panzar and Willig, 1982, p. 178). Following the discussion of these two properties I present a short summary of other conditions which were found to be sufficient for subadditivity in the multiple output case. I then present the necessary condition for subadditivity.

2.1.2.1 Ray Average Costs

In the single output case, average cost is computed using Cost divided by Output. In the multiple output case, there is no clear divisor for this equation. Hence, in the multi-product case, average cost is not a clearly defined concept.

We can measure the average costs of production along a ray from the origin, a concept known as ray average cost (Panzar, 1989, p.10). This is accomplished by determining the total cost at a point along the ray and dividing that figure by a measure of the index of output along the ray. If this measure is found to be declining as output increases, the cost function is said to exhibit declining ray average cost. This can be written as:

$$\frac{C(v\,y_1, v\,y_2)}{v} \le \frac{C(w\,y_1, w\,y_2)}{w}, \quad for\ v > w \tag{1.6}$$

where w and v are measures of the index of output along a ray through an output vector (y_1, y_2) (Panzar, 1989, p. 11). Note that the index measure used is not important, it may be simply a percentage of all outputs. The important property in the above equation is the inequality, which yields declining ray average costs.

Now, it is interesting to note that economies of scale are a sufficient condition for declining ray average costs. To see this, recall from section 2.0.2 that economies of scale exist if:

$$C(vy) < vC(y)$$

If we take the definition of declining ray average costs, let w=1 and multiply through by v we obtain:

$$C(vy) \leq vC(y)$$

From this, it is easy to see that economies of scale form a sufficient[1] but not a necessary condition for declining ray average costs. This insight will become of great importance in the next section, but first, a discussion of transray convexity is in order.

2.1.2.2 Transray Convexity

Transray convexity is readily explained with the aid of a diagram. In Figure 1.2, the cost surface of a multi-product monopolist is represented by the hyperplane ABCD. A ray extends from the origin along Dc. Another ray, a transray, intersects the ray Dc along acb. When this transray is extrapolated up to the cost hyperplane it cross-sectionalizes the cost surface

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1 Indeed, notice that economies of scale implies strictly declining ray average costs.

at ACB. The cost hyperplane along this transray cross-sectionalization (ACB) is convex in this case (Baumol, Panzar and Willig, 1982, p. 83). A cost surface is said to be transray convex if the extrapolation of any transray up to the cost surface yields a convex cross-sectionalization of the cost surface.

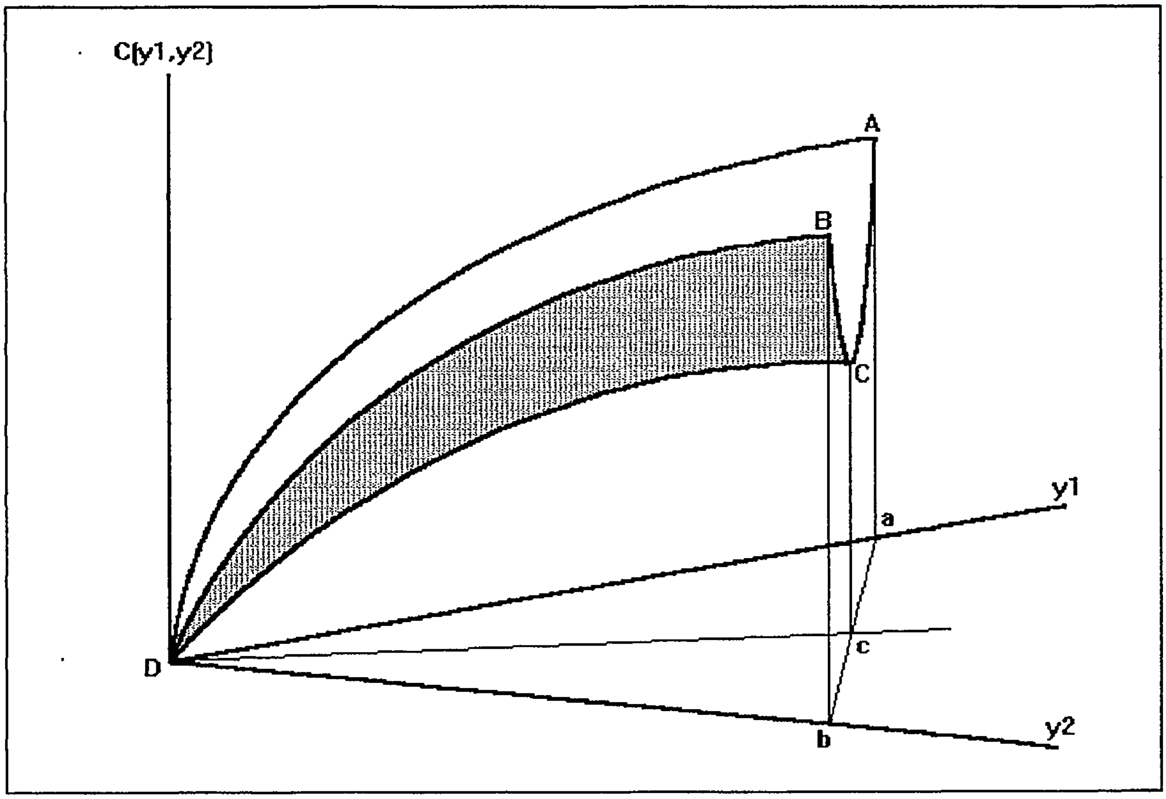

Figure 1.2

It is important now to consider the mathematical representation of transray convexity as this will enable us to determine the necessary and sufficient conditions for subadditivity. Fortunately, we may use Figure 1.2 to aid in the mathematical development of this property. For simplicity, let $C(\alpha)$ represent any point on the cost hyperplane along the transray acb between a and c including a. Let $C(\beta)$ represent any point on the cost hyperplane along the transray acb between b and c including b. Further, let $C(\gamma)$ represent the total costs of producing output vector c. Then, transray convexity may be represented mathematically as:

$$C(\gamma) = C(k\alpha + (1-k)\beta) \leq kC(\alpha) + (1-k)C(\beta), \quad for\ 0 < k < 1$$

This indicates that a line connecting $C(\alpha)$ with $C(\beta)$ must not lie below the cost surface anywhere between the two points α and β.

Note that for transray convexity to exist, this need only hold true for one transray cross-section of the cost hyperplane[1] through output vector γ, even though an infinity of such cross-sections exist. Also note that a cost surface which is transray convex at any one point need not be transray convex at any other point (Baumol, Panzar and Willig, 1982, p.81).

Now consider that if a cost function exhibits both strictly declining ray average costs and transray convexity, then that curve also exhibits subadditivity. That is, the combination of these two properties yields a sufficient condition for subaddivity and a natural monopoly to exist. An insightful proof of the fact that transray convexity (when combined with strictly declining ray average cost) implies subadditivity is presented below[2].

The mathematical representation of strictly declining ray average costs may be manipulated into a useful form. Specifically, from Equation (1.6) if we let w=1 and v=k, strictly declining ray average cost can be represented as:

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1 Any $0 < k < 1$.

2 The following proof follows (Baumol, 1977), with complete development and commentary by the author of this work.

(1.7) $$C(k\gamma) < kC(\gamma)$$

Now, if we maintain the same definitions of α and β as above and further allow these output vectors to be related via: $k\gamma=\alpha$, $(1-k)\gamma=\beta$, k is a scalar (which can be represented with the scalars p and t via: $k = 1/p$, and $(1-k) = 1/t$) we can write equation (1.7) (strictly declining ray average costs) as:

$$kC(\gamma) > C(\alpha)$$

Using k and p, we can write this as:

(1.8) $$kC(kp\gamma) > C(kp\alpha)$$

Further, if Equation (1.8) holds, then

$$(1-k)C(\gamma) > C(\beta)$$

also holds. Using the definitions of (1-k) and t, we can write this as:

(1.9) $$(1-k)C((1-k)t\gamma) > C((1-k)t\beta)$$

Adding (1.8) and (1.9) together yields:

(1.10) $$kC(kp\gamma) + (1-k)C((1-k)t\gamma) > C(kp\alpha) + C((1-k)t\beta)$$

When we add transray convexity to this representation of decreasing ray average cost, depicted in Equation (1.10), we will see that subadditivity is guranteed.

Now, turning our attention to transray convexity, this property requires:

(1.11) $$C(k\alpha + (1-k)\beta) \leq kC(k\gamma) + (1-k)C((1-k)\gamma)$$

If we scale the arguments of C ,α and β, in equation (1.11) by the same factors p and t, respectively then inequality (1.11) continues to hold <u>if the cost function is transray convex over the entire domain of C</u>. Equation (1.11) becomes:

(1.12) $$C(kp\alpha + (1-k)t\beta) \leq kC(kp\gamma) + (1-k)C((1-k)t\gamma)$$

Notice that the left hand side of (1.10) is the same as the right hand side of (1.12). Combining (1.10) and (1.12) yields a condition which holds when both transray convexity and strictly decreasing ray average cost are present:

$$kC(kp\gamma) + (1-k)C((1-k)t\gamma) \geq$$
$$C(kp\alpha) + C((1-k)t\beta) > C(kp\alpha + (1-k)t\beta)$$

Now, as kp=1 and as (1-k)t=1 by construction, it follows that:

$$kC(\gamma) + (1-k)C(\gamma) \geq C(\alpha) + C(\beta) > C(\alpha + \beta)$$

which implies:

$$C(\alpha) + C(\beta) > C(\gamma)$$

which is the definition of subadditivity.

In summing up, strictly decreasing ray average costs and transray convexity together form a sufficient condition for subadditivity and for natural monopoly to exist. As well, because economies of scale implies strictly decreasing ray average costs, it follows that economies of scale and transray convexity suffice for subadditivity.

The logic upholding the notion that subadditivity results from the combination of transray convexity and strictly decreasing ray average cost is ingenious. If the cost function exhibits transray convexity over the entire domain of C, and exhibits strictly declining ray average costs, then the cost function must have a shape similar to the one depicted in Figure 1.2. Viewing this from the top gives us the perspective viewed in Figure 1.3 (assume that transray convexity yields strictly concave isocost curves though this need not be the case). Strictly decreasing ray average costs guarantees that the ray

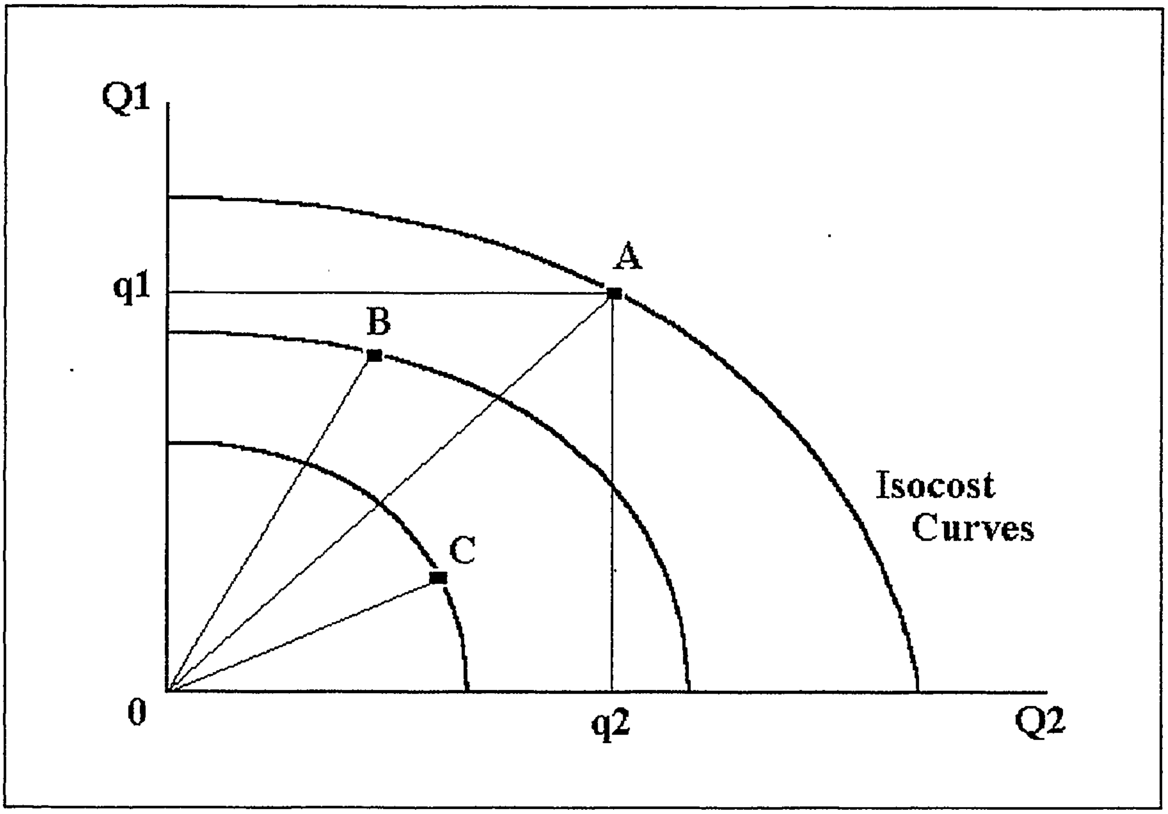

Figure 1.3

average cost of producing output bundle A (consisting of q1 quantity of product Q1 and q2 amount of product Q2) is minimized at A. That is, joint production of q1 and q2 can not be achieved cheaper than at point A by using production involving any combination of points along 0A[1] because average costs are decreasing along this ray. However, production expansions do not always follow rays from the origin, and for this reason we need to consider the shape of the cost surface away from this ray. Combining transray convexity with strictly decreasing ray average costs guarantees that the isocost curves will expand from the origin in a certain way. In particular, they will expand

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1 This argument applies with equal weight to points B and C along rays 0B and 0C, respectively.

in such a way as to guarantee that production of q1 and q2 can not be achieved cheaper by any combination of production bundles off the ray 0A. As an example of this phenomenon, suppose that production of bundles B and C sum to q1 and q2. Suppose further that the costs of production of bundle B and C are \$3 and \$4, respectively. Transray convexity combined with decreasing ray average costs guarantees that the isocost curve of \$7 will lie beyond point A.

It is also interesting to consider the economic conditions which can yield transray convexity. Baumol, Panzar and Willig (1982, p.82) hold that transray convexity exists if average incremental costs,

$$\left[\textit{defined as:}\ \ AIC_i = \frac{C(y_i, y_j) - C(0, y_j)}{y_i} \right],$$

of each product are increasing and if there exists weak cost complementarities. They further suggest that decreasing marginal cost (which is evidence of product specific scale economies) is consistent with transray convexity only if cost complementarity is sufficiently strong (Baumol, Panzar and Willig, 1982, p. 82).

It must be noted that there exist other sets of cost properties which suffice for subadditivity. An example of this is that if a firms cost function exhibits economies of scope and product-specific scale economies[1] (which exist if the average incremental cost for product i are decreasing as the output of good i increases). In this case, economies of scope means that it is cheaper

1 These economies measure the change in costs through variation in the output of one product while holding the quantities of other products constant. Note that firms with increasing product specific economies of scale have a cost incentive to expand the production of this product, and may become specialized in its production (Squires 1988, p.363)

to produce the set of products together while product specific scale economies implies subadditivity in each product line (Waterson, 1988, p. 26). Another sufficient condition is cost complementarities[1]. If increasing the production level of one output results in decreased marginal costs for another jointly produced product then joint production is more favourable than separate production (recall example in section 2.0.3). Further, if this phenomenon exists over all output levels, then larger production levels will result in lower marginal costs than lower production levels. If this is the case, then the cost of producing total industry output is minimized when a single large firm is engaged in production.

The importance of this is that the existence of these other sufficient conditions for subadditivity alert us to the fact that transray convexity and strictly decreasing ray average cost form a sufficient but not a necessary condition for subadditivity. Notice that if transray convexity is not present, cost complementarities may still be present and hence a natural monopoly may exist.

To summarize the sufficient conditions for subadditivity in the multiple output case, consider the following. Ray average cost provides information on multi-product cost structures, specifically, ray average cost provides a measure of total cost divided by output-weighted marginal costs. This index is a proxy for average cost in the multiple-output setting. As well, the concepts of decreasing ray average costs and economies of scale are

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1 A mathematical proof of this may be found in Gravelle and Rees, 1992, p. 228.

synonymous. Transray convexity allows us to examine the shape of the cost hyperplane between rays from the origin. This allows us to examine possible cost complementarities in production[1]. However, we must be aware that if transray convexity fails to exist, it is possible that the cost surface still exhibits cost complementarities, and hence a natural monopoly may still exist. Consequently, the absence of transray convexity and/or economies of scale does not necessarily exclude the the existence of a natural monopoly.

2.2 Necessary condition for natural monopoly

Economies of scope have been found to be a necessary condition for subadditivity. We now turn our attention to this cost function characteristic.

2.2.1 Economies of Scope

Economies of scope is a necessary but not a sufficient condition for global subadditivity to exist. This follows from the mathematical definition of economies of scope given in section 2.0.2,

$$C(y_1, y_2) < C(y_1, 0) + C(0, y_2)$$

From this, economies of scope is seen to be a special case of subadditivity,

$$C(y_1, y_2) < C(\hat{y}_1, \hat{y}_2) + C(\tilde{y}_1, \tilde{y}_2)$$

where each hypothetical firm specializes in the production of one output of the monopolist. If economies of scope exist then subadditivity exists, but only[2]

1 Which in the case of pipelines may arise due to shared compressors and pipe in producing several transportation services.

2 Recall from section 2.0.1 that a cost curve may exhibit regions of (continued...)

when $\hat{y}_2, \tilde{y}_1 = 0$. Economies of scope is therefore a necessary but not a sufficient condition for subadditivity and, because of this, we may not conclude that subadditivity exists from a test of economies of scope alone.

It is interesting to note that even when economies of scale and scope are combined, they still do not provide a sufficient condition for global subadditivity. Hence, the presence of both of these cost function characteristics does not allow us to conclude that subadditivity exists. To see this, consider the cost function given as:

$$C(y_1, y_2) = \sqrt{y_1 + y_2} - e$$

(e will be defined later as the firm's fixed costs. Consider for now that e is equally applicable to both the joint and separate production of both products.)

Economies of scope requires that the cost of separate production is strictly greater than the cost of joint production,

$$\sqrt{y_1 + y_2} - e < \sqrt{y_1} + \sqrt{y_2} - 2e$$

Manipulating this, we can obtain:

$$\sqrt{y_1 + y_2} < \sqrt{y_1} + \sqrt{y_2} - e$$

Further manipulation yields:

$$e < \sqrt{y_1} + \sqrt{y_2} - \sqrt{y_1 + y_2}$$

Now note that as:

$$\sqrt{y_1} + \sqrt{y_2} \geq \sqrt{y_1 + y_2}, \quad \sqrt{y_1} + \sqrt{y_2} - \sqrt{y_1 + y_2} \geq 0, \quad \textit{for all } (y_1, y_2) \geq 0$$

e may be negative[1]. If we suppose that e is negative then an economic

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2(...continued)
subadditivity, additivity and superadditivity at the same time.

1 Negative e will be required later for economies of scale.

interpretation of e exists. We may think of e as some type of licensing fee, or start up cost. This fee must be paid out regardless of the type of production, joint or separate, which is to take place. The presentation of subtracting a negative number, though slightly confusing, greatly facilitates the following proof.

Economies of scale requires that:

$$\frac{\sqrt{y_1+y_2} - e}{(y_1+y_2)(y_1+y_2)^{1/2}} > 1$$

If e is negative, some start up costs are incurred in production, this holds true as long as at least some production takes place. If this is the case, then the cost function exhibits both economies of scale and scope.

Subadditivity requires:

$$\sqrt{y_1+y_2} - e < \sqrt{\hat{y}_1+\hat{y}_2} + \sqrt{\tilde{y}_1+\tilde{y}_2} - 2e$$

where overscores denote two different firms and subscripts denote products. If we choose a positive number, n, arbitrarily small so that:

$$e + n = \sqrt{y_1} + \sqrt{y_2} - \sqrt{y_1+y_2}$$

we may write the subadditivity requirement as:

$$\sqrt{y_1} + \sqrt{y_2} - n < \sqrt{\hat{y}_1+\hat{y}_2} + \sqrt{\tilde{y}_1+\tilde{y}_2}$$

Notice that this holds true only if $\hat{y}_2, \tilde{y}_1 = 0$, which means that each firm specializes in the production of each output (for an n arbitrarily small).

As e, the firms' fixed costs, get smaller[1] there is a greater likelihood of the above inequality holding true for partitions of the monopolists output

1 The cost function properties of economies of scale and scope remain unaffected by this.

other than $\hat{y}_2, \tilde{y}_1 = 0$. If economies of scope and scale together formed a sufficient condition for subadditivity then the size of the firms fixed costs should be irrelevant. The fact that we require small fixed costs to make the above inequality hold true for partitions other than $\hat{y}_2, \tilde{y}_1 = 0$ provides evidence that economies of scale and scope together do not provide a sufficient condition for global subadditivity to exist. It then follows that the presence of economies of scale and scope do not allow us to conclude that subadditivity exists.

Economies of scale (which imply strictly decreasing ray average costs) and economies of scope are not strong enough to guarantee subadditivity. Though economies of scope provide sufficient evidence for one special partition of the monopolists output, we need to consider other partitions of the monopolists output to guarantee global subadditivity. Simply adding the property of economies of scale to the cost function does not allow us to consider these other partitions of the monopolists output.

As a result of this analysis regarding multiple output production, we are aware that the presence of economies of scope does not allow us to conclude that subadditivity exists. In addition to this, we know that the absence of transray convexity and/or economies of scale does not allow us to conclude that subadditivity does not exist. Consider the follwoing tables for summaries of the necessary and sufficient conditions for subadditivity disclosed in this Chapter.

Table 2.1 Necessary and Sufficient Conditions for Subadditivity in the Single Output Case

Property	Necessary Condition	Sufficient Condition
Economies of Scale	×	✓

Table 2.2 Necessary and Sufficient Conditions for Subadditivity in the Multiple Output Case.

Property	Necessary Condition	Sufficient Condition
Economies of Scale	×	×
Economies of Scope	✓	×
Economies of Scale and Economies of Scope	✓	×
Transray Convexity	×	×
Decreasing Ray Average Costs	×	×
Transray Convexity and Decreasing Ray Average Costs	×	✓
Cost Complimentarities	✓	✓
Product Specific Scale Economies	×	×
Product Specific Scale Economies and Economies of Scope	✓	✓

With this analysis of the theory of natural monopoly behind us, we may make a hypothesis regarding the natural monopoly status of TCPL, but first we should consider how the theory of natural monopoly applies to TCPL.

2.3 Relevance to TCPL

The standard rationale for the existence of a natural monopoly is that economies of scale (firm) exist. This approach may be true for the pipeline industry. Mansell and Church hold that there are several reasons why we should expect to find economies of scale in pipeline technologies. They define a property, volumetric returns to scale[1]:

> As the diameter of a pipeline doubles, its volume goes up by a factor of four, while its surface area increases by a factor of two. Output is proportional to volume while cost of construction is generally proportional to surface area. (1995, p.15).

They further suggest that some construction costs are invariant to the size of pipeline expansion and consequently larger expansions can lower average cost. Mansell and Church also state that the size of rights-of-way[2] vary disproportionately with pipeline size expansions, and that there may be economies of organization[3] in pipeline technologies (1995, p.16).

It is also quite likely that TCPL incurs economies of scope. Recall that economies of scope can arise from large common costs and cost

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1 See also Varrian (1992, p. 15)

2 This is a legal term meaning that the pipeline company has the right to install and access its facilities without necessarily owning the land that the pipeline sits on.

3 Optimal network configuration and optimal management (involving activities like rerouting, aggregating and sharing transmission) are more likely to occur if there is only a single firm.

complementarities. According to Sharkey,

> if there is common machinery or equipment used in producing two or more outputs (such as compressors or pipe producing several transmission services), then cost complementarity would fail to hold if capacity constraints on individual machines become binding (1982, p.70).

Thus, we expect cost complementarities to exist in pipeline technologies as long as the pipeline is not running at full capacity. Further to this, Mansell and Church suggest:

> Besides giving rise to economies of scale, this factor (volumetric returns to scale) is also responsible for economies of scope. Construction of one pipeline to provide service from Empress to Winnipeg and another to provide service from Empress to Toronto is more costly than constructing one pipeline to provide service to both (1995, p. 15)

Given that both volumetric returns to scale and cost complementarities are expected to be experienced by TCPL, it follows that we expect TCPL to experience economies of scope.

Transray convexity can arise, as Baumol, Panzar, and Willig suggest, from cost complementarities and increasing average incremental cost (product specific economies of scale). We expect TCPL to experience cost complementarities, but it is unknown whether or not TCPL experiences this particular form of economies of scale. As a result of this, it is unknown whether or not TCPL's cost structure will display transray convexity.

Now a hypothesis can be formed regarding the natural monopoly status of TCPL. If we consider TCPL to be a single output monopolist[1], and suspect that TCPL experiences economies of scale, we can hypothesize that TCPL is a natural monopolist. Additionally, if we consider TCPL to be a multiple output monopolist[2], which we suspect experiences cost complementarities (a sufficient condition for subadditivity), we can maintain the hypothesis that TCPL is a natural monopoly.

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1 This single output could be total deliveries of natural gas.

2 We may consider natural gas delivered to different locations or gas delivered under different service contracts to be different products and thus that TCPL is a multiple product monopolist.

CHAPTER THREE: TESTS FOR NATURAL MONOPOLY

3.0 Introduction

Several problems arise which must be dealt with before any econometric testing for a natural monopoly can be attempted. This chapter shows the econometric methodologies which can be used to test the theory presented in Chapter two, and exposes the limitations of these econometric methodologies in the current context. In short, the previous chapter is about what we would like to do, this chapter is about what we can do.

This chapter presents some cost theory, a functional form which can be used in estimating a cost function, and the procedures which must be employed to determine whether or not estimation of this functional form yields a legitimate cost function. This is followed by a discussion of econometric problems which exist when we use this functional form, and an explicit discussion of the application of both Baumol, Panzar and Willig's (1982) test and the Evans and Heckman (1984) test for natural monopoly (subadditivity) using this functional form.

3.1 Cost Functions

Unfortunately in empirical work we often do not know the underlying technology that a firm uses, consequently we also do not know a priori the true functional form of the cost function. Economic theory does, however, provide us with some advice when it comes to selecting a functional form for the cost function. Under the behavioural assumption of cost minimization; the firm's cost function is defined by:

$$C(y,w) = \min\ [wx,\ such\ that\ x \geq 0,\ \phi(x,y) \geq 0]$$

(Varrian 1992, pp. 73, 76-77)

The cost function is characterized by four restrictions.

1. It is concave in prices.

$$C(y,(tw^{o} + (1-t)w^{i})) \geq tC(y,w^{o}) + (1-t)C(y,w^{i})$$

Where: C is the cost function.

y is a vector of outputs.

t is any number between zero and 1.

w^{o} and w^{i} are two different price vectors.

Varrian provides intuition for this cost function restriction[1].

> If the price of a factor rises (holding other factor prices constant), costs will never go down, but they will go up at a decreasing rate ... because as this one factor becomes more expensive ... the cost minimizing firm will shift away from it to use other inputs (1992, p.73).

2. It is homogeneous of degree one in prices.

$$C(y,tw) = tC(y,w)$$

Homogeneity of degree one in prices conveys the idea that a proportional

---

1 A mathematical proof of this is provided in Appendix 2.

change in all prices will require a proportional change in cost (at a constant level of output). This follows from the fact that if all prices change proportionately then the cost minimizing bundle of inputs will not change. If the composition of the input bundle does not change and all prices rise by a certain proportion, then cost must also rise by that proportion.

3. It is non-decreasing in prices (monotonicity),

$$\frac{\partial C(y,w)}{\partial w_i} \geq 0, \ \forall i$$

Non-decreasing in prices means that if any input price increases, holding output constant, the costs of production can not drop. This can be explained with the following argument. If an input price increases then some substitution away from this input may occur. If this happens, and total cost drops, then the firm could have lowered its costs by preforming some substitution of inputs before the price change occurred. This implies that the firm could not have been cost minimizing before the price change. If the firm is cost minimizing then total cost can not drop if an input price increases.

4. It is increasing in output,

$$\frac{\partial C(y,w)}{\partial y} > 0$$

Increasing in output states that as the scale of output increases, holding input prices constant, an increase in the scale of inputs is required. This increase in the scale of inputs results in increased costs of production. In the single product case this implies that marginal cost is strictly positive, however, positive marginal cost is not required in the case of multiple output production. Shephard (1970, p.227) provides this regularity condition for the multiple output production case:

$$C(y,w) < C(\theta y,w); \ \forall\theta\in[1,\infty)$$

This states that as the scale of output is increased cost must increase, which implies that economies of scale must be positive.

Positive scale economies can (but need not) follow from strictly positive marginal costs. Panzar's measure of scale economies in the multiple output case is:

$$S(y,w) = - \frac{\left[\lambda \sum x_i{}^* \frac{\partial \phi(x,y)}{\partial x^*}\right]}{\left[\lambda \sum y_j \frac{\partial \phi(x,y)}{\partial y_j}\right]} = \frac{C(y,w)}{\sum y_j C_j(y,w)}$$

If all C_j are positive then it is guaranteed that $S(y,w) > 0$, however, not all C_j need be positive for this to hold.

An intuitive argument for this result is available. In the multiple output case, if all output quantities are increased proportionately, then the use of at least some inputs must increase (if not, the firm is not cost minimizing), and hence cost must rise. However, it may be possible to increase the production of one output while actually decreasing inputs[1], and lowering costs. Conditions under which we would expect to observe this phenomenon are discussed in Chapter Five. For now it is sufficient to recognize that in the multiple output production case, marginal cost need not

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1 Consider the case where one output has no value (economic or social) which must be disposed of (Shephard, 1970, p. 187). If a market is found for this product it may be possible for the firm to increase the production of this output at a cost lower than the cost of disposal.

be positive, though economies of scale must be strictly positive[1].

The restrictions on the cost function do not define a functional form which may be used for estimation purposes, but merely restrict the search to a certain class of functional forms. Flexible functional forms are a particularly useful sub-class of these functions. In this section, I discuss the translog flexible functional form and its application to cost function estimation.

A flexible functional form provides a second order approximation of the true cost function. Thus, using one of these forms means that the exact shape of the function is unknown at the time of estimation - but may be approximated after the parameters of the function are estimated.

A number of flexible functional forms have been suggested for use in econometric research. The most popular, for its simplicity and ease of application, is known as the trans-log flexible functional form (Braunstein and Pulley, 1992, p. 222).

The trans-log function is based upon the Taylor series expansion, which expands the function in every direction away from the data points (Chiang, 1984, pp. 256-259). A second order Taylor series expansion for the cost function is written as;

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1 For a more rigorous proof of this, see Appendix 3.

$$C(w,y) = \frac{C(w_o, y_o)}{0!} + \frac{C'(w_o, y_o)}{1!}((w,y) - (w_o, y_o)) +$$

$$\frac{C''(w_o, y_o)}{2!}((w,y) - (w_o, y_o)^2) + R$$

(Chiang, 1984, p. 258)

where w_o and y_o are the vectors around which the cost function is expanded. We then take the variables from this equation, apply natural logarithms and assume that the Lagrange form of the remainder (R) is subsumed into the OLS residual vector (e). This yields an explicit functional form:

$$\ln(C) = \alpha_o + \Sigma_i \alpha_i \ln(w_i) + \Sigma_k \beta_k \ln(y_k) +$$

$$\frac{1}{2}\Sigma_i \Sigma_j \gamma_{ij} \ln(w_i) \ln(w_j) +$$

$$\frac{1}{2}\Sigma_k \Sigma_l \delta_{kl} \ln(y_k) \ln(y_l) +$$

$$\Sigma_i \Sigma_k \rho_{ik} \ln(w_i) \ln(y_k) + e$$

(Johnston, 1984, p.335)

Additionally, we may apply Shephard's Lemma to this function. This procedure yields cost share equations which may be jointly estimated with the translog cost function (this results in an increase in the degrees of freedom). Explicitly, the cost share equations in this application are derived from the translog function by application of Shephard's Lemma via:

$$As\ \frac{\partial C}{\partial w_i} = x_i,$$

$$S_i = \frac{w_i x_i}{C} = \alpha_i + \Sigma_{ij} \gamma_{ij} \ln\ (w_j) + \Sigma_k \rho_{ik} \ln(y_k)$$

(Johnston, 1984, p.336)

3.1.1 Restrictions and Tests Using the Translog Form

Symmetry[1] and homogeneity are easily imposed upon the translog form while monotonicity, concavity and increasing in output must be tested.

To impose symmetry on the translog form, we must set:

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

while homogeneity of degree one can be imposed via the restrictions:

$$\Sigma_j \alpha_j = 1, \quad \Sigma_j \gamma_{ij} = 0, \quad \Sigma_j \rho_{jk} = 0, \ \forall \ i,j,k$$

(Evans, 1983, p. 255)

Monotonicity (non-decreasing in prices), concavity in prices and increasing in output can be tested using non-parametric tests (Shin and Ying, 1992, p.176). Monotonicity is tested by evaluating the partial derivative of the cost function with respect to input prices, and evaluating this derivative at each observed data point. Increasing-in-output is tested by evaluating economies of scale (at each observation) of the cost function.

Concavity is tested using the Hessian matrix. According to Chiang,

> A twice continuously differentiable function $z = f(x_1, \ldots, x_n)$ is concave if, and only if, d^2z is everywhere negative semidefinite.

---

1 If the factor demand equations are derived from the cost function via Shephard's lemma, and they are jointly estimated with the cost function, then each parameter of the factor demand equations must equate to the corresponding parameter of the cost function.

> The said function is <u>strictly</u> concave if (but not only if[2]) d^2z is everywhere negative definite (1984, p.347).

When twice differentiated with respect to input prices, the cost function has the following quadratic form:

$$\textit{for } \boldsymbol{C} = f(w,y), \quad d^2\boldsymbol{C} = \sum_{i=1}^{x} \sum_{j=1}^{x} f_{w_i w_j} dw_i dw_j$$

where x is the number of input prices in the function. Assuming two input prices, the Hessian has the following principal minors:

$$|D1| = |f_{w_i w_i}|, \quad |D2| = \begin{vmatrix} f_{w_i w_i} & f_{w_i w_j} \\ f_{w_j w_i} & f_{w_j w_j} \end{vmatrix}$$

(Chiang, 1984, p.333)

Given these principal minors,

> The corresponding necessary-and-sufficient condition for negative definiteness (strict concavity) is that the principal minors alternate sign as follows:
>
> $$|D1| < 0, \quad |D2| > 0, \quad |D3| < 0, \quad etc.$$ [2]
>
> (Chiang, 1984, p. 325)

However, strict concavity is a much more stringent condition than the concavity requirement of economic theory. Concavity may be tested by

---

1 Negative definintness grantees strict concavity, but negative semidefinitness does not disallow strict concavity.

2 Note that D1 < 0 implies that all second order own partial derivatives of the cost function (with respect to input prices) must be negative. By application of Shephard's lemma, this implies that all factor demand equations must be downward sloping, as regularity condition 3 presented in Section 3.1 states.

evaluating the Eigenvalues[3] of the Hessian matrix (which is the largest principal minor presented above). Chiang states that a function "...is negative semidefinite, if and only if all characteristic roots of (the Hessian matrix) are nonpositive (1984, p. 330)." Thus, the cost function is concave if the characteristic roots of the Hessian matrix are zero or are negative.

Both tests for concavity and strict concavity will be executed in Chapter five to be certain that this regularity condition holds true.

In addition to these regularity conditions, other hypotheses regarding the underlying production technology and cost properties can be tested using this functional form. These hypothesis (and their test formulation) are presented in Table 3.1, reproduced in part from Evans (1983, p. 256).

Table 3.1 Cost Characteristic Tests Using the Translog Form.

Hypothesis	Cost function Characteristics	Translog parameter restrictions
Separability of inputs and outputs	$C(y,w) = C[A(y),w]$	$\rho_{il}\beta_k = \rho_{ik}\beta_l$ $k \neq l$
Nonjointness	$C(y,w) = \Sigma C_i(y_i,w)$	$\delta_{kl} = -\beta_k\beta_l$ $k \neq l$

1 These are values (of r) which satisfy the characteristic equation: $|H - rI| = 0$. Where H is the Hessian matrix and I is the (of appropriate dimension) identity matrix.

Homotheticity	$C(y,w) = A(y)g(w)$	$\rho_{il} = 0$
Homogeneity in outputs	$C(k^r y,w) = k^r C(y,w)$	$\rho_{il} = 0, \ \delta_{kl} = 0$

3.1.2 Specification Tests Using the Translog Form

It is of interest that under parameter restrictions the translog form can be used to derive other functional forms. For example, the familiar Cobb-Douglass function,

$$C(w,y) = w^{\alpha} y^{\beta}$$

can be derived from the trans-log function by setting:

$$\gamma_{ij} = 0, \ \delta_{ki} = 0, \ \rho_{jk} = 0$$

This restriction can be tested after estimation or imposed on the cost model at the time of estimation.

3.1.3 Problems with the Translog form

Although there are many advantages to using this form, there are some disadvantages. The most serious limitation of the translog form in this application is expressed by Braunstein and Pulley. They state that:

> ... a well-known disadvantage of the log-quadratic output structure of the translog model is its inability to model cost behaviour when any output is zero. As a result, the estimated translog cost function cannot be used to measure the costs of

specialized production, as is required to estimate economies of scope or product-specific economies of scale[1] (1992, p.222).

As the translog form is unable to model cost behaviour when any output is zero, product specific economies of scale and economies of scope are not directly measurable using this form. To get around this problem, we could set the appropriate measure of output arbitrarily close to zero then test for the presence of economies of scope. Braunstein and Pulley (1992) investigated this procedure when they estimated several different flexible functional forms to answer questions regarding scope economies in banking. One of the functions they used was the familiar translog form. Using this function, they allowed measures of quantity to be close to zero in their economies of scope test (which permitted the translog function to produce an estimate). However, they found that estimates of scope economies were highly variable depending upon the arbitrary (and close to zero) value assigned to their measures of quantity. In particular, they found economies of scope estimates of 0.14 and 3460.5 when their output measures were 0.25 and 0.0001 respectively (Braunstein and Pulley, 1992, p. 229). As a result of this, Braunstein and Pulley found that they could not obtain reliable estimates of economies of scope by using the translog function with output measures arbitrarily close to zero.

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1 As declared in Chapter Two, economies of scope and product specific economies of scale form a set of necessary and sufficient conditions for subadditivity.

3.2 Operationally Performable Tests of Natural Monopoly Using the Translog Form.

We now turn our attention to the operational performance of tests for natural monopoly which we can reliably accomplish using the translog functional form. We begin with a discussion of Baumol, Panzar and Willig's (1982) tests and finish with the Evans and Heckman (1984) test for subadditivity.

3.2.1 Baumol, Panzar and Willig's test of Necessary and Sufficient Conditions.

Baumol, Panzar and Willig argue that the necessary and sufficient conditions for a natural monopoly can and should be tested. They also assert that it may be impossible to determine global subadditivity due to informational requirements, but that it is still possible to test for the presence of natural monopoly. Baumol, Panzar and Willig claim:

> ... unlike the property of scale economies at y, subadditivity at y cannot be conclusively assessed from data about costs only in the vicinity of y. The cost surface must be scrutinized not merely in the neighbourhood of that point, but also all the way to the axes and the origin. ... We cannot know whether an industry is a natural monopoly for the production of the output vector y if we have no information ruling out the possibility that many small firms (or several intermediate-sized firms or some

> combination of the two) can produce y more cheaply than can a single producer. Thus to prove subadditivity, we must have information on the costs of every potential small or intermediate producer; and that is why we must know the cost function for a firm for every (possible output vector smaller than y) (Baumol, Panzar and Willig, 1982, p. 171).

Clearly the data requirements to prove global subadditivity are daunting. With this data problem, Baumol, Panzar and Willig claim that there is still a legitimate way to go about testing for subadditivity, by empirically testing the various sets of necessary and sufficient conditions for subadditivity (Baumol et al., 1982, p. 172). These conditions follow, with the econometric methodologies used to test them.

In the single output monopolist case, we must test for economies of scale (knowing that this forms a sufficient but not a necessary condition for subadditivity and hence a "natural" monopoly to exist). If economies of scale exist there is sufficient evidence to conclude that the monopoly is a "natural" one. If we fail to find economies of scale, we may conclude that the monopolist has expanded production beyond the minimum efficient scale of production. In this case, we do not know if industry costs would be minimized by the presence of a monopolist or two firms. In this case, the economies of scale test yields inconclusive results.

In the case of a multiple output monopolist, we test for economies of scale and transray convexity. This test includes a direct test for cost complimentarities, and an indirect test for economies of scope.

Testing for economies of scale is accomplished via standard techniques. First, the monopolists cost function is econometrically estimated and then the formulae in Section 2.2 are applied using relevant output vectors and input prices. These formulae are reproduced below for clarity. In the single output case, the formula is:

$$(y,w) = \frac{C(y,w)}{y\,C_y} = \frac{C(y,w)}{y} * \frac{1}{C_y} = \frac{AC}{MC}$$

While in the multiple output case, the formula is:

$$S(y,w) = -\frac{\left[\lambda \Sigma x_i^* \dfrac{\partial \phi(x,y)}{\partial x^*}\right]}{\left[\lambda \Sigma y_j \dfrac{\partial \phi(x,y)}{\partial y_j}\right]} = \frac{C(y,w)}{\Sigma y_j C_j(y,w)}$$

where y is the vector of outputs and w is the vector of input prices. These formulae are evaluated at each observed data point to determine the presence of economies of scale.

Turning now to transray convexity, Squires provides an econometrically applicable test for this cost function characteristic. Squires states:

> Cost convexity (increasing average incremental costs) and weak cost complementarity are sufficient conditions for transray convexity. Roughly speaking, a cost function is transray convex if, as a firm changes the composition of output while holding fixed the level of some aggregate measure for output,

costs will be lower for diverse rather than specialized output mixes. Overall transray behaviour is difficult to test with either cost or profit functions, but testing for pairwise transray convexity is straightforward. If transray convexity does not exist among all product pairs, then transray convexity does not hold. (This) indicates that either one of the following conditions is sufficient for transray convexity between outputs i and j:

$$C_{ii} \geq 0,\ C_{jj} \geq 0,\ C_{ij} = C_{ji} \leq 0,\ \forall\ i \neq j, \text{ or,}$$

$$C_{ii} \leq 0,\ C_{jj} \leq 0,\ C_{ij} = C_{ji} \leq 0,\ C_{ij} \leq -\sqrt{C_{ii}\,C_{jj}}$$

(1988, p. 365)

Here C_{ii}[1] ≥ 0 implies that the cost function is convex in product i, and $C_{ij} \leq 0$ implies weak cost complementarities. Note that $C_{ii} \leq 0$, which suggests the presence of product specific scale economies, can only be consistent with transray convexity if C_{ij} is sufficiently negative (cost complementarity is sufficiently strong) (Baumol et al., 1982, p. 82).

This test can be applied to the translog flexible functional form to evaluate trans-ray convexity.

In addition, these transray convexity tests allow us to test for economies of scope. We can not use the translog form to directly test for economies of scope, but we may indirectly test for the presence of this property. Recall from Chapter two that cost complementarities suffices for economies of scope. If we find (while preforming the transray convexity test) cost complementarities then we may conclude that TCPL experiences economies

1 The cross partial derivative with respect to one output.

of scope.

3.2.2 Evans and Heckman Subadditivity Test

In contrast to Baumol, Panzar and Willig, Evans and Heckman suggest a direct test for subadditivity. Evans and Heckman define subadditivity as:

$$\Sigma_i \, C(a_i q_1, b_i q_2) > C(q_1, q_2), \quad i = 1 \ldots n$$

$$\Sigma a_i = 1, \quad \Sigma b_i = 1, \quad a_i \geq 0, \quad b_i \geq 0$$

for at least two a_i and b_i not equal to zero (Evans and Heckman, 1984, p. 616). Note that if all a and all b sum to one then the combined output of all firms equals the output of the monopolist. Also the cost function is superadditive if, in the first equation above, ">" is replaced with "<" (Evans and Heckman, 1984, p.616).

In the case when the alternative industry structure is two firms replacing the monopolist, Evans and Heckman operationally define their test for subadditivity as:

$$Sub_t(\zeta, \omega) = \frac{[C_t - C_t^A(\zeta, \omega) - C_t^B(\zeta, \omega)]}{C_t}$$

where: ζ, ω are the ratios of each product being produced (assuming two products are produced) by each firm in excess of the minimum production level for which we have data.

C_t is the cost predicted at time period t.

Superscripts A and B refer to the two firms under consideration.

This test for subadditivity is quite straightforward. From the definition of subadditivity, if a cost function exhibits subadditivity then,

$$C_t < C_t^A(\zeta,\omega) + C_t^B(\zeta,\omega)$$

Which implies that:

$$C_t - C_t^A(\zeta,\omega) - C_t^B(\zeta,\omega) < 0$$

Further division by C_t yields a measure, Sub_t, which is the percentage cost savings obtainable from the current market structure relative to the alternative. The cost function is subadditive if the predicted percent cost savings, Sub_t, are negative.

Note that this prediction may be performed for multiple years for which we have data, and for multiple output distributions between hypothetical firms. However, testing the entire cost surface for subadditivity is an unnecessary exercise as Evans and Heckman point out.

> In many situations the interesting statistical question concerns whether the cost function is additive or subadditive at observed output levels. The cost function is subadditive, superadditive, or additive if and only if the cost function is subadditive, superadditive at all relevant output vectors q. The relevant output vectors are those which are consistent with industry equilibrium given demand and cost conditions for alternative possible organization patterns of the industry (for example, multifirm vs. single firm) (1984, p. 617).

Thus only those relevant output vectors must be tested for subadditivity rather than the entire cost surface. This implies that the Evans and Heckman test of subadditivity is a local one, and not a global test.

Evans and Heckman further qualify their test by placing restrictions upon the relevant output vectors which may be tested. The rationale for these restrictions is that the hypothetical industry output configurations should be within the range of output configurations actually observed in the data. This will avoid excessive extrapolation outside the data for hypothesis testing (Evans and Heckman, 1984, p. 617). There is no strong econometric evidence that these restrictions need be imposed as statistical theory will merely adjust the confidence intervals of the test if we predict outside the available data set. However, these restrictions have some validity. Testing within the data set offers the virtue that if the cost function is found to be superadditive, then there exists an alternative industry configuration which consists of hypothetical firms operating within the historical parameters of the existing monopolist. Further, a prediction which states a certain industry configuration will result in lower cost of production is completely useless if the industry configuration is not technologically feasible. This is a concern which may arise if one extrapolates outside the available data set. These restrictions are simply ones which force us to make predictions which are known to be technologically feasible. We now expand these restrictions in more detail.

The first restriction is that no firm is permitted to produce less (of each output) than the lowest output level of the monopolist. This imposes the restriction that the subadditivity test may only be performed in a region where the production of each product is at least twice that of the minimum observed production level of the monopolist. To emphasize this restriction, consider that there are two firms which must share production of each product. If neither firm is permitted to produce below the minimum production level of the monopolist, then both firms must jointly produce at least twice the minimum production level of the monopolist. Fortunately, recall from Chapter One that TCPL's production has more than doubled in the past 5 years. With the data available it should be possible to test TCPL for subadditivity in the relevant range of current production levels.

The second restriction Evans and Heckman (1984) place upon their subadditivity test is that both firms must produce both products within a ratio observed in the data. The lower limit is the lowest ratio of production between two product lines and the upper limit is the highest ratio. This restricts each firm from specializing in either output to a greater extent than the existing monopolist.

3.3 Conclusion

This chapter has presented the regulatory conditions for a cost function, a flexible functional form for use in econometric estimation, and the econometric methodologies for testing these conditions using this functional form. This was followed by a discussion of econometric problems which exist when we use this functional form, and an explicit discussion of the application of both Baumol, Panzar and Willig test and the Evans and Heckman test for a natural monopoly. Before we proceed with econometric estimation using TCPL data, a brief overview of previous studies using this methodology will be presented.

CHAPTER FOUR: PREVIOUS STUDIES

4.0 Introduction

Several attempts have been made at estimating a cost function to test the natural monopoly status of an industry and this chapter presents a review of the relevant literature. We examine the telephone industry as an introduction to the applied work of testing for natural monopoly, and to review the development of more recent applied techniques. Next, we examine work conducted for the pipeline industry. For the pipeline industry, only two previous studies are available and summaries of both are presented here.

4.1 Telephones

The most acknowledged work in this field is that performed with respect to the telephone industry. Five notable studies have been performed in this area. Two of these were conducted using Bell Canada data (Smith and Corbo, 1979 and Fuss and Waverman, 1981). The remaining were conducted using US data (Evans and Heckman, 1983, Roller, 1990 ,and Shin and Ying, 1992).

4.1.1 Canadian Telephone Studies

Common to both Canadian studies was the data set and that flexible functional forms were used to estimate cost functions. In the Canadian studies, annual data was obtained for the period 1952 to 1976 to estimate multiproduct cost functions of Bell Canada.

Smith and Corbo (1979) estimated a standard trans-log flexible cost function and tested for aggregate scale economies[1]. Smith and Carbo found evidence to support aggregate scale economies, but did not discuss the possibility of Bell Canada being a natural monopoly.

In contrast, Fuss and Waverman (1981) estimated a more generalized trans-log flexible functional form with quantity variables entered as $Q_i=(Q^a-1)/a$. This subsumes the standard translog functional form as the limit of $(Q^a-1)/a$, as a tends to zero, is ln(Q), which is the quantity variable in the translog function. Fuss and Waverman tested the significance of the variable: a, and rejected the standard trans-log functional form. They also found that their more general functional form showed that Bell Canada did not exhibit aggregate scale economies. Further this special functional form allowed Fuss and Waverman to test for economies of scope, which can not be performed using the standard trans-log flexible functional form (described inChapter Three). After performing these tests, Fuss and Waverman concluded:

> There is little evidence that Bell Canada is a natural monopoly with respect to all of its principal service offerings. In particular, tests of overall economies of scale and tests of economies of scale and scope with respect to private line services fail to reject the hypothesis that private line services can be provided on a competitive basis without efficiency loss (Evans, 1983, p.146).

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1 These are present when a proportionate change in all outputs leads to a less than proportionate change in costs (Evans, 1983, 154).

Two points should be noted about these studies. First, the results of the economies of scale test changed under different flexible functional form specifications. This implies that care must be exercised when choosing a functional form to estimate, and that it is possibly better to select the most general functional form in order to avoid estimating a misspecified model.

Second, neither of these studies provides sufficient evidence for the existence or non-existence of natural monopoly in the Canadian telephone industry. As shown in Chapter Two, under multiple output production economies of scale forms a special condition for subadditivity (required for one sufficient condition), but is neither a necessary, nor a sufficient condition by itself. Despite Smith and Carbo providing evidence that Bell Canada exhibits economies of scale, and thus that Bell Canada exhibits decreasing ray average costs (an insufficient condition for subadditivity), this is insufficient evidence for the existence of natural monopoly.

Further, although Fuss and Waverman perform tests for economies of scale and scope, they perform an inappropriate natural monopoly test. If diseconomies of scope and scale are observed, this indicates that Bell Canada is not a natural monopoly. However, if economies of scope and economies of scale exist, the logical conclusion is that there is insufficient evidence to conclude that Bell Canada is a natural monopoly. The tests of economies of scale and scope allow one to conclude that Bell Canada IS a natural monopoly, but does not allow one to conclude that Bell Canada is NOT a natural monopoly. Fuss and Waverman utilized these tests to fail to reject their non-natural monopoly hypothesis. This conclusion can be drawn regardless of the results of any tests of economies of scale or scope.

4.1.2 U.S. Telephone Studies

The US studies, by Evans and Heckman, Roller, and by Shin and Ying, were more successful in providing evidence concerning natural monopoly.

Evans and Heckman (1984) attempted to test the natural monopoly status of the Bell Telephone Company. They obtained annual data for the period 1947 to 1977 from Christensen and Cummings (1981). The data obtained included operating revenue for five categories of service: local, interstate tolls, intrastate tolls, directory advertising, and miscellaneous. Quantity data was derived from the revenue data and price indices supplied by AT&T. Evans and Heckman used the Tornqvist procedure to calculate output indices for local and long distance services in order to obtain two output measures from the data. Local calls consisted of the categories: local, directory advertising, and miscellaneous; while long distance consisted of both interstate and intrastate categories (Evans, 1983, p. 275). Additionally, data was available on the number of hours worked by, and wage rates paid to, Bell system employees. From this data an index of the price of labour and labour's share in Bell's costs was calculated. Information on the carrying costs of 20 different assets was obtained from Christensen and Cummings (1981). From this data cost shares and an index of capital price was calculated using the Tornqvist procedure. Attempts were made at deflating cost data by an R&D specific deflator rather than the CPI, but this resulted in poor statistical estimates. The Evans and Heckman complete data set on the Bell system is available in Evans (1983, pp. 276, 277)

Evans and Heckman estimated three different flexible cost functions: a standard translog cost curve; a modified translog function; and a Box-Tidwell cost function. The modified translog function followed Fuss and Waverman (Evans, 1983, p.146). The Box-Tidwell function is a more general function following the transformation Fuss and Waverman used, with the transformation being applied to all variables in the estimated equation instead of just output variables.

For the standard translog equation, an iterative and an autoregressive iterative Zellner procedure were used in estimation. For the other two functions nonlinear seemingly unrelated regressions was used via the full information maximum likleyhood procedure. The estimates for the non-autoregressive flexible functions are presented in Table 4.1.

Table 4.1 Parameter Estimates from Evans (1983, p. 259).

Parameter	Translog		Modified Translog		Box - Tidwell	
Constant	9.057	(1.96)	9.054	(.004)	9.054	(.004)
Capital	.536	(.004)	.537	(.004)	.537	(.004)
Labour	.354	(.004)	.354	(.004)	.353	(.003)
Local	.294	(.261)	.260	(.350)	.542	(.204)
Toll	.420	(.197)	.462	(.299)	.110	(.140)
Technology	-.161	(.070)	-.193	(.108)	-.008	(.073)
$Capital^2$	.197	(.024)	.190	(.027)	-.145	(.085)
$Labour^2$	.176	(.025)	.171	(.027)	-.028	(.037)

Capital * Labour	-.163	(.021)	.158	(.023)	-.246	(.027)
Toll^2	-5.276	(1.700)	-6.531	(4.905)	-2.999	(1.432)
Local^2	-2.640	(1.132)	-3.951	(4.118)	.491	(.567)
Local * Toll	7.764	(2.700)	10.233	(8.828)	-2.87	(1.185)
Tech.^{2}	.412	(.799)	-.126	(1.547)	-2.60	(.424)
Capital * Toll	.354	(.097)	.399	(.131)	.264	(.045)
Capital * Local	-.352	(.089)	-.390	(.114)	-.374	(.034)
Labour * Toll	-.221	(.087)	-.263	(.116)	-.038	(.028)
Labour * Local	.209	(.080)	.244	(.103)	.104	(.016)
Capital * Technology	.106	(.037)	.119	(.044)	-.006	(.008)
Labour * Tech.	-.108	(.034)	-.120	(.039)	.020	(.074)
Tech. * Toll	-.967	(1.204)	-1.924	(2.990)	2.440	(1.062)
Tech. * Local	.358	(1.202)	1.513	(3.130)	-.678	(.498)
nu	---	---	-.031	(.114)	.725	(.110)

Note: Standard errors are in parenthesis and parameters significant at the 5% level are underlined.

Evans and Heckman evaluated their translog function by testing regularity conditions. Initially, they imposed homogeneity and symmetry on the system of equations, but rejected these restrictions, calculating a test statistic of 210.97 compared to a critical chi squared of 32.7 (21 df). Evans and Heckman state that this result:

> ... may indicate that the translog cost function is a poor approximation to the true cost function, that the cost function is

> misspecified in some other basic way, or that firms do not behave as assumed by producer theory (Evans, 1983, p. 263).

Unable to resolve this conflict, Evans and Heckman impose homogeneity and symmetry on the estimating system[1]. Separability was tested and rejected (with a test statistic on the translog equation of 11.73 compared to a critical chi squared of 5.99 (2 df)) indicating that a single output measure (i.e. an aggregate index of output) was not consistient with the data. This implied that single output cost function for the Bell system data was not appropriate. Next, Evans and Heckman evaluated own price factor demand elasticities and concluded that these, "... were negative for every year between 1947 and 1977[2] (Evans, 1983, p. 264)" as is expected from theory.

Lastly, Evans and Heckman applied their subadditivity test to all data points that satisfied their restrictions i.e. the years 1958 to 1977 inclusive. As the subadditivity test involved splitting up production of the monopolist between two firms, Evans and Heckman decided to apply a grid search pattern of applying this test to the Bell system data. Output one was distributed between the two firms in increments of 10% while the distribution of output two was held constant. The distribution of output two was altered by 10% and the procedure was repeated until all unique distributions of output between the two firms were addressed. For the two outputs and two firms used in this test, this equates to 25 separate tests for local subadditivity per year. Evans

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1 Note that table 4.1 presented above contains parameter estimates obtained under the imposition of homogeneity and symmetry.

2 This represents the entire data set

and Heckman performed a total of 475 separate tests for local subadditivity for each equation estimated (translog and autoregressive translog, restricted and unrestricted). This testing algorithm resulted in the following conclusion:

> We found that the Bell System did not have a natural monopoly over any of the output configurations which were realized between 1958 and 1977. Two firms were always able to produce these output configurations more cheaply than a single firm (Evans, 1983, p. 272).

The advantage of this procedure is a direct test for subadditivity which can be applied to existing data sets. In previous research, one needed a data set which covered the complete history of the monopolist to be used in testing for natural monopoly. Given the importance of this new research, Evans and Heckman published this procedure in the American Economic Review in September 1984 in addition to publishing the complete work in 1983.

Following the work of Evans and Heckman, Roller, 1990 and Shin and Ying, 1992 made significant contributions in this field.

Roller argued that Evans and Heckman failed to properly test the cost function before performing their subadditivity test, and in using the translog flexible functional form.

Roller's first comment stems from Baumol, Panzar and Willig (1982). Roller stated:

> A proper cost function must be nonnegative and linearly homogeneous, concave and nondecreasing in input prices. In addition, when the assumption of free disposal is made, a proper cost function must be nondecreasing in outputs (Roller, 1990, p. 203).

Roller also criticized the use of the translog functional form for its inability to provide reliable estimates of stand alone costs[1], and hence its inability to estimate economies of scope (a necessary but insufficient condition for natural monopoly). In lieu of this functional form, Roller suggested that a generalized Constant Elasticity of Substitution cost function be used as this functional form allowed stand alone costs and economies of scope to be measured. This also allowed the natural monopoly tests to be performed on a cost function which was restricted to be linearly homogeneous, although Roller made no mention as to whether or not he tested this restriction in his study.

To see if the natural monopoly results reported by Evans and Heckman would change if this methodology was followed, Roller estimated a CES cost function using the full information maximum likleyhood procedure with data published by Evans and Heckman. Roller tested for global concavity and positive marginal cost[2] in his analysis, and dropped the points failing these tests from the natural monopoly analysis. Roller found economies of scale, economies of scope, and using the Evans and Heckman subadditivity test,

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1 Stand alone costs are those costs which would be incurred if the production of each output was conducted separately rather than jointly.

2 Recall from Chapter three that this is a sufficient but not a necessary regularity condition for a multiple output cost function.

reported that he found subadditivity when the points failing concavity and positive marginal costs were dropped from the analysis.

Roller's contribution to the analyses, and to the conclusion regarding the natural monopoly status of the US telephone industry, is subject to criticism. It is a legitimate criticism (by Roller) of the work performed by Evans and Heckman that they should have satisfied all the conditions for a legitimate cost function. However, recall from Chapter three that the legitimacy conditions of a multiple output cost function include concavity and increasing in output and do not include positive marginal cost. Although dropping observations which do not satisfy concavity is legitimate, dropping observations which do not satisfy positive marginal cost can result in the loss of some completely legitimate information[1]. In addition, Roller estimates a different flexible functional form from that estimated by Evans and Heckman. As Roller estimates a different functional form, and possibly deletes some information for illegitimate reasons, Roller's study does not tell us how the Evans and Heckman conclusion would change if all the regularity conditions were satisfied.

The different conclusions reached by Roller and by Evans and Heckman seem to come from different interpretations of the subadditivity test. Evans and Heckman interpret their test quite strictly, requiring their test statistic

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1 Recall from Chapter three that positive marginal cost is a sufficient but not a necessary regularity condition for a legitimate multiproduct cost function. Requiring positive marginal cost will guarantee that increasing in output is satisfied, however, positive scale economies will also guarantee this, and do so without requiring positive marginal costs.

to be significantly negative in order to provide evidence for subadditivity. Conversely, Roller does not provide confidence intervals around predictions of cost savings that would be realized from breaking up the Bell Company, but merely presents negative subadditivity test results. If this econometrically questionable practice was applied by Evans and Heckman, they also could have concluded that the US telephone industry was a natural monopoly.

Shin and Ying provide the most recent analysis of the US telephone industry. A major problem with previous studies was limited data available for analysis. Shin and Ying collected annual pooled cross section time series data on 58 local exchange carriers for the time period 1976 to 1993. This data set consists of a total of 464 observations, compared to the previous two US telephone studies (Evans and Heckman, 1983, and Roller, 1990) which used only 31 annual observations.

Shin and Ying collected a number of variables:

* Total cost; expenses for factors excluding capital, derived by taking operating expenses less depreciation.
* Capital expenditures; gross plant after deflating. Annual interest and depreciation costs of capital are derived from this figure assuming that depreciation is constant over the life of the plant.
* Price of labour; compensation per employee.
* Price of capital; variable capital expenditures divided by the average number of telephones.
* Three output variables: the average number of phone lines and output

usage measures which consisted of local calls and toll calls.

* Technology variables; dummy variables applied to the estimated cost curve to differentiate different types of firms in the pooled data.
* A time trend variable; to account for general technology improvements and the general trend toward more phone lines being added to networks during this period (Shin and Ying, 1992, p. 175).

Shin and Ying estimated a standard translog cost curve under the following rationale. They state that even though Roller has made a well informed criticism regarding regularity conditions, there is a trade-off between properness and flexibility of the estimated equation. Shin and Ying argued:

> Since the point of these studies is to determine the technological structure, we feel that sacrificing flexibility is too high a price to pay for properness. Rather than possibly creating bias by incorrectly estimating the underlying technology, we have chosen to preserve flexibility by estimating a translog cost function with the correct technology, and to check for regularity conditions and non-negative marginal costs afterwards (Shin and Ying, 1992, p. 173)

Shin and Ying imposed homogeneity and symmetry during estimation. After estimation they tested for monotonicity, concavity and positive marginal costs. Of the 464 observations, 6 violated monotonicity, 18 violated concavity, and 31 had negative marginal costs[1], all of these observations were deleted from the subadditivity tests. Allowing for overlapping test failures, there remained 421 of the original 464 observations for the subadditivity test (Shin and Ying, 1992, p.176). The results obtained by Shin and Ying are reprinted in Table 4.2.

Table 4.2 Parameter estimates from Shin and Ying (1992, p. 182).

Equation	R-Square
Total Cost	0.9977
Labour Share	0.2682
Capital Share	0.5187

Parameter	Estimate	Std. Error	Parameter	Estimate	Std. Error
Intercept	-.0137	.0150	PK * CO	-.0112	.0044
PL	.3651	.0069	PK * EA	.0002	.0007
PK	.5213	.0065	PK * AL	-.0348	.0088
TL	.6953	.0428	PK * B	-.0343	.0056
LO	.1686	.0282	PK * T	.0061	.0010
TO	.0773	.0178	TL * LO	-.0779	.0677
CO	.0256	.0115	TL * TO	.0563	.0344
EA	-.0089	.0026	TL * CO	-.0372	.0218
AL	.1439	.0291	TL * EA	-.0014	.0024
B	.0262	.0129	TL * AL	-.1306	.0375
T	-.0125	.0032	TL * B	.0758	.0254
$\frac{1}{2}PL^2$	.1591	.0024	TL * T	.0163	.0041
$\frac{1}{2}PK^2$	.1783	.0022	LO * TO	-.0163	.0198
$\frac{1}{2}TL^2$	.0324	.1086	LO * CO	.0589	.0153
$\frac{1}{2}LQ^2$	.0575	.0446	LO * EA	.0013	.00162

1 Note that as stated above, deleting observations for negative marginal costs will guarantee that increasing in output is satisfied, however, positive marginal cost is not required for a legitimate multiproduct cost function.

$\frac{1}{2}TO^2$	-.0201	.0161	LO * AL	.0824	.0246
$\frac{1}{2}CO^2$	.0086	.0080	LO * B	-.0293	.0173
$\frac{1}{2}EA^2$	-.0018	.0003	LO * T	-.0118	.0026
$\frac{1}{2}AL^2$	.0472	.0216	TO * CO	-.0252	.0065
$\frac{1}{2}T^2$	.0014	.0004	TO * EA	.0028	.0012
PL * PK	-.1436	.0021	TO * AL	.0283	.0161
PL * TL	.0954	.0159	TO * B	-.0322	.0109
PL * LO	.0617	.0106	TO * T	-.0019	.0018
PL * TO	.0259	.0067	CO * EA	-.0027	.0011
PL * CO	.0036	.0043	CO * AL	.0163	.0123
PL * EA	.0006	.0007	CO * B	.0069	.0097
PL * AL	.0557	.0096	CO * T	-.0019	.0011
PL * B	-.0064	.0059	EA * AL	-.0026	.0019
PL * T	-.0082	.0010	EA * B	.0194	.0046
PK * TL	.1138	.0157	EA * T	.0003	.0002
PK * LO	-.0555	.0103	AL * B	.0315	.0160
PK * TO	-.0382	.0064	AL * T	-.0087	.0027
			B * T	-.0029	.0017

Where: PL = labour price, PK = capital price, TL = access lines, LO = local calls, TO = toll calls, CO = central offices, EA = % electronic access, AL = average loop length, B = Bell indicator, and T = time trend. Also note that all variables significant at the 5% level are underlined.

Applying the Evans and Heckman subadditivity test to the above three output model results in 365 separate tests for subadditivity for each of the 421 observations. Of the possible 21,170 separate tests for 1983 only, Shin and Ying found that in only one third of the cases was it possible for a monopoly to provide service cheaper than two firms. Due to space limitations, the entire results of this extensive search could not be published, but Shin and Ying summarized their results, which are reproduced in Table 4.3.

Table 4.3 Summary statistics with Positive Marginal Costs and Minimum Output Bounds by Year (Shin and Ying, 1992, p.179).

		Monopoly Costs Lower than Two-Firm Costs		Savings from having a Monopoly[a] (Percent)			
Year	Possible Cases	N	Percent	Minimum	Maximum	Average	Std. Error
1976	16045	3192	19.9	-33.38	2.72	-3.61	.036
1977	16196	3553	21.9	-32.97	2.67	-3.46	.035
1978	15798	3801	24.1	-31.92	2.80	-3.15	.034
1979	15043	3887	25.8	-30.26	2.75	-2.79	.032
1980	13610	3817	28.0	-28.46	2.83	-2.40	.031
1981	10744	3412	31.8	-25.12	2.70	-1.77	.029
1982	10340	3315	32.1	-25.46	2.74	-1.72	.029
1983	11324	3164	27.9	-25.78	2.58	-1.85	.028

[a] Positive values indicate subadditivity (natural monopoly) negative values indicate superadditivity.

Shin and Ying use these results to justify their conclusion that local exchange carriers in the US are not natural monopolies.

To summarize the investigation of the natural monopoly status of the U.S. Bell Telephone Company we review the summary statistics and results of these studies. This is followed by a summary of the contributions to this line of research which were made while investigating the U.S. Bell Telephone Company.

In the US telephone studies presented here there is little variance in the summary statistics presented. R^2 figures, adjusted and unadjusted, in all the studies are around 0.99 for the cost curve and around 0.96 for share equations. Durbin Watson statistics, despite a variance in the degrees of freedom associated with this statistic across studies, show possible first order autocorrelation. Various authors have corrected for this problem in their estimation algorithms. Finally, all of the studies, after carefully analysing their merits, show the same conclusion; that the US telephone industry was not a natural monopoly.

It is worth noting that some significant contributions were made to applied natural monopoly theory as a result of this line of investigation. We now have available to us a direct test of subadditivity due to the work performed by Evans and Heckman. We have Roller's contribution that we should be aware of producer theory when performing this type of work, and Shin and Ying provided us with a method of applying producer theory without sacrificing the flexibility of the translog functional form.

4.2 Pipelines

We now turn our attention to previous studies performed using pipeline data. There have been two studies of note that use flexible functional forms to investigate the cost structure of the pipeline industry. In one study, Aivazian, Callen, Chan,and Mountain (1987) estimated a translog production function to answer questions regarding technological change in the aggregate U.S. pipeline industry. On the other hand, Ellig and Giberson (1993) estimated a translog cost function to measure economies of scale and scope in the intrastate (Texas) gas transmission industry. Brief summaries of these studies are presented below, in turn.

Aivazian et. al. (1987) proposed in their study to estimate a production function for the interstate transmission of natural gas in the US to determine economies of scale and answer questions regarding technological change. Annual data was collected on 14 major interstate natural gas transmission companies from regulating agencies for the period 1953 to 1979. This data included input measures for labour, line-pipe capital, horsepower capital, and fuel. The output measure consisted of the amount of gas delivered (in cubic feet) multiplied by the length of the line (Aivazian et al., 1987, p. 558).

Aivazian et. al. used the functional form: $Q = F(X, T)\, c^{a}$, where: Q is industry output measured in cubic feet miles, X is the input vector, T is a time index used to measure technical change, and c is a constant[1] (Aivazian et al., 1987, p. 557). As a translog approximation to this implicit form yields a non-linear explicit form, maximum likelihood estimation procedures are used in estimation.

Aivazian et. al. define their output measure to be amount of gas transported over some distance. This is the correct measure of output and should be used in studies involving pipeline transportation technologies.

Another useful piece of information presented in the Aivazian et. al. study is an estimate of the scale economies in the U.S. gas transmission industry. Aivazian et. al. provide an estimate of the overall economies of

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1 Assuming that the function is homogeneous of degree a.

scale of 1.911 (Aivazian et. al., 1987, p. 559). Further, Aivazian et. al. state:

> ... 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 analysis of the gas transmission industry. 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 (Aivazian et al., 1987, p. 556).

There are two concerns with this upper limit of 2.07. Aivazian et. al. obtain this estimate from an engineering study performed in 1972[1]. It is possible that recent technological advances in compressor technology may have increased the upper limit. Second, with regard to TCPL, there is a source of inefficiency that may result in an estimate of scale economies below 2.07. Theoretically the measure of economies of scale whether derived through a production function or a cost function are identical, however, this equality need not hold in practice. Evans and Heckman state:

> There are two basic problems with engineering studies. First, these studies ignore the costs of managing the firm and thereby ignore the possibility that managerial diseconomies may outweigh engineering economies. Many technologies exhibit engineering

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1 Robinson, S. T., (1972), "Powering of Natural Gas Pipelines", Journal of Engineering for Power, A.S.M.E. Transactions 94 (July), 181-186

scale economies. Yet few industries are considered natural monopolies. Bureaucratic inefficiencies generally swamp engineering economies from large-scale operations (Evans, 1983, p. 140).

Therefore, we expect to measure TCPL's scale economies near 2.07, but may be higher due to technological advances, and may be lower due to bureaucratic inefficiencies.

Ellig and Giberson (1993) use data on the intrastate transmission of natural gas in Texas to measure economies of scale and scope across 50 Texas pipelines over two years (1989-90).

They collected cross-sectional data from the Texas regulating agency which consisted of: operating costs, depreciation, amortization, taxes, the cost of gas purchased[1], commercial and industrial sales in millions of cubic feet (mmcf), sales for resale (mmcf), volume of gas transported for others (mmcf), total gas throughput (mmcf), and miles of pipe (Ellig and Giberson, 1993, p. 83).

They then defined two modified[2] translog cost functions according to the

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1 In Texas, regulators permit pipelines to purchase natural gas for resale purposes.

2 Note that the modifications to the standard translog form that Ellig and Giberson make include the omission several cross terms, the omission of the premultiplication of squared terms by one half, and the inclusion of a total output variable. It is significant to note that the rationale for (continued...)

following rationale:

> One dependant variable is the natural log of operating and maintenance costs, which generally include all operating costs except depreciation, amortization and taxes. In essence, this specification can be considered a short-run cost function[1]. The other estimate employs (the natural log of) operating costs as the dependent variable; operating costs include operation and maintenance costs plus depreciation, amortization, and taxes. This second equation is the closest to a long-run cost function[2] that the data permit us to estimate. Strictly speaking, this would be a long-run cost function if pipelines could adjust their capacity instantaneously, and if the depreciation and amortization schedules chosen for accounting purposes accurately reflected economic depreciation and amortization. Because of these complications, we will refer to this second equation as the "quasi-long run" cost function (Ellig and Giberson, 1993, pp. 82-83).

Using ordinary least squares to estimate cost equations (no share equations)

2(...continued)
this procedure given is "...when throughput (total output) is left out, gas transported for others consistently has negative marginal cost (1993, p.89)."

1 In essence, the level of capital is held constant when the cost of capital is not included in the measure of cost.

2 In this case, capital costs are included in the measure of cost and hence levels of capital are allowed to vary. The resulting cost function is then a long-run cost function.

they provide estimates shown in Table 4.4.

Table 4.4 Parameter Estimates from Ellig and Giberson (1993, p. 85).

Parameter	Short-Run Equation	t-statistic	Quasi-Long run Equation	t-statistic
Commercial Sales	.15	1.51	.07	.062
Commercial Sales2	.002	.28	.006	.65
Sales for resale	.11	1.09	-.02	.16
Sales for resale2	.01	1.14	.02	1.74
Transportation Volume	.16	1.45	.15	1.27
Transportation Volume2	-.029	3.26	-.03	2.95
Throughput	-.20	.23	.34	.35
Throughput2	.05	1.36	.28	.65
Commercial * Resale	-.018	3.26	-.013	2.12
Commercial * Transport	-.006	.77	.004	.43
Resale * Transport	-.002	.30	.002	.18
Price of Gas Purchased	-.26	.70	-.69	1.62
Miles of Pipe	.03	.56	.09	1.72
Constant	5.42	**	3.15	**
Adj R-squared	0.82		.74	
Durbin-Watson[1]	2.04		1.86	

** not reported
Note: parameter estimates significant at the 5% or better level are underlined.

Ellig and Giberson also reported estimates of multiproduct economies of scale in the range of 7.25 to 0.37. Note that in only one of the reported cases do they estimate a value greater than 2.07, and in only 3 of the 40 reported

1 Recall that Ellig and Giberson use cross-sectional data in their study, hence insignificant Durbin Watson statistics are expected.

cases do they estimate measures greater than 1.0. Though the one estimate of 7.25 is questionably high, all other reported estimates fall below 2.07. This seems to support the previous argument that we should expect a value in the neighbourhood of 2.07 when this test is applied to the TCPL data.

Even though it is well known that the translog specification does not provide reliable estimates of cost when output is restricted to be zero, Ellig and Giberson provided estimates of overall economies of scope and product specific economies of scale (both of which require zero output measures). They found overall diseconomies of scope (0.35) and one case of product specific economies of scale in the resale of purchased natural gas (3.12) (Ellig and Giberson, 1993, p. 86).

With the absence of overall economies of scale and general absence of economies of scope, Ellig and Giberson concluded that these results seem to point toward the conclusion that intrastate natural gas transmission is not a natural monopoly in Texas. They state: "The Texas experience implies that the move toward direct pipeline competition need not generate social waste (Ellig and Giberson, 1993, p. 88)."

4.3 Summary

The work discussed in this chapter has provided some relevant concepts to apply to the TCPL study. Evans and Heckman (1984) have provided us with an econometrically applicable direct test for local subadditivity. Roller (1990) has cautioned us to be aware of producer theory, and Shin and Ying

(1992) have provided us with methodology which allows us to preserve flexibility in the translog functional form without sacrificing properness. The work done by Aivazian et. al. (1987) has provided an operational definition of output variables, which should be applied to work of this nature. As well the work preformed by Aivazian et. al. (1987), Evans (1983), and Robinson (1972) have provided arguements which suggest a reasonable range for the economies of scale test results. As a result of their work, we can expect a measure in the neighbourhood of 2.07 when this test is applied to TCPL. Finally, Ellig and Giberson (1993) have provided us with an operational definition of long run costs which can be applied to the TCPL data.

CHAPTER FIVE: CURRENT STUDY

5.0 Introduction

In this chapter, I present some problems with the current study, the available data, TCPL cost function estimates, natural monopoly test results and an answer to the question; "Is TCPL a natural monopoly."

5.1 Problems with the Current Study

There are two problems with the current study. These are with regard to negative marginal costs, and whether or not we are dealing with a long-run or a short-run cost curve.

The first problem I deal with is the matter of negative marginal cost. Recall from Chapter Three that it is not a requirement of a legitimate multiple output cost function that all marginal costs be positive. Here it is appropriate to discuss conditions under which we would fully expect to observe a company producing at output levels where not all marginal costs are positive. Note that this phenomenon has been observed in the literature by Ellig and Giberson (1993).

Ordinarily we would never expect a company to produce in a region where a marginal cost was negative as this company could produce a little more of one of its products and lower total costs as a result. (Note that negative marginal cost implies that a greater output bundle can be produced at lower cost. It does not imply that the same output bundle can be produced at lower cost, and hence does not imply that the firm is not cost minimizing when producing at negative marginal cost.) However, the problem with this procedure is that the increased production must be dispersed. Optimally, the company in question would like to sell this output, but if this is not possible then this excess output must be discarded. Roller (1990, p. 203) states, "... when the assumption of free disposal is made, a proper cost function must be non-decreasing in outputs (marginal cost must not be negative)." Thus it is the case that only when excess production can be sold or freely discarded do we expect to observe strictly positive marginal costs in multiple output production.

The phenomenon of negative marginal cost is not as strange as it first appears. As an example consider a single output firm which produces 6 units of output with a vector of inputs. Suppose that when the firm increases its utilization of one input that production drops to 4 units. As would be the case if labour showed negative marginal product. Suppose further that the cost of disposal of 2 units exceeds the cost of incremental labour. The cost minimizing method of producing 4 units involves the larger work force, with no units of output being disposed. Meanwhile, the cost minimizing method of producing 6 units of output involves the smaller work force, and total cost decreases with output is expanding from 4 to 6 units. Thus, if disposal is not free, negative marginal costs may exist.

In the case of TCPL, the output of TCPL is a service and production can not occur unless the outputs are either sold or discarded. If sale is not possible, then discarding is the only other alternative. However, this is not a viable alternative for TCPL. To fathom this, consider the outputs of TCPL. These outputs are transportation services differentiated by type and by location of delivery. Notice that discarding excess product implies that TCPL transport excess gas to one of its delivery points, and then discard that transportation (as the natural gas delivered is not demanded at the end of the pipe). Discarding this excess transportation implies that the delivered natural gas also be discarded, and there is a problem with accomplishing this. Given that the natural gas industry in Canada is a regulated one, approval will be required to discard this resource. Further, given that there are user costs associated with the production of natural gas, this approval is unlikely to be forthcoming.

If TCPL can not dispose of additional natural gas then the free disposal assumption of economics is violated. The result of this violation is that it is possible for TCPL to experience negative marginal cost. Negative marginal cost, if observed in the production of one or more of TCPL's outputs, should be interpreted thus; the market for these products is of insufficient size to allow TCPL to take full advantage of cost savings obtainable from increased production.

The next problem I deal with is the distinction between the long-run and the short-run in this study. Given that we wish to estimate a long-run cost curve, and that the data we have consists of short-run observations, a clear distinction must be made as to which cost curve (long or short-run) we are estimating. If we assume that TCPL adjusts its inputs optimally in the short-run, then the following diagram is appropriate.

short-run, then the following diagram is appropriate.

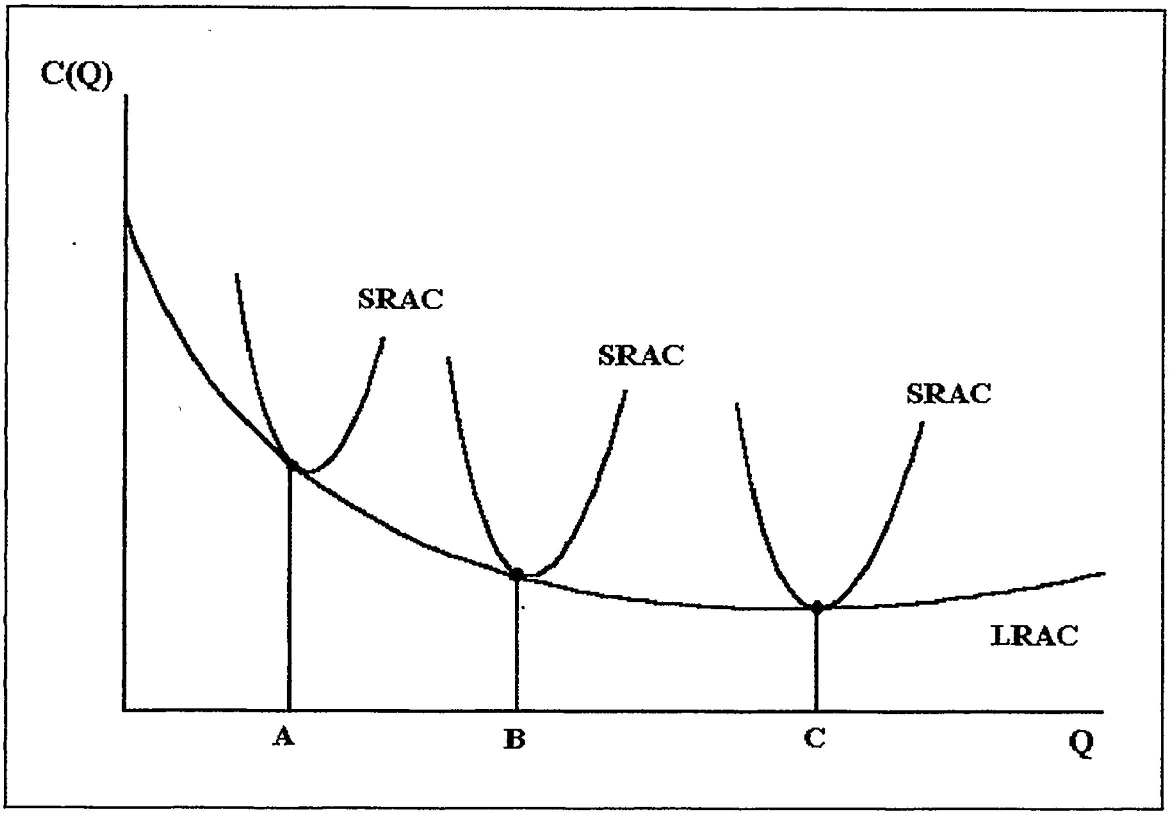

Figure 5.1

In Figure 5.1, we have the case of a single output market where C(Q) represents the cost of producing a quantity of output, Q. LRAC is the market long run average cost curve and SRAC is the family of short run average cost curves. (We could draw an analogous diagram involving total cost curves, but this representation yields non-overlapping curves without loss of generality.) Now, if TCPL is the only producer in this market, and adjusts its inputs optimally in the short run, then the short run output quantities A, B, and C are produced with costs incurred as presented in Figure 5.1. Notice that these points map out, or envelope, the long run average cost curve. Hence, if TCPL optimally adjusts its inputs in the short run then the connection of short run observations will yield a long run cost function.

However, it may be the case that TCPL has not adjusted its inputs optimally in the short run. Consider the following argument. Given that a certain size of pipe is already in place, if an expansion is to occur the fact that a pipe is already in place may affect the cost of the expansion. Suppose a pipe is in place which has the capacity to transport 1000 m^3 of natural gas per hour over some distance. Suppose further that an increase in capacity is required in the amount of 100 m^3 per hour. The cheapest long-run solution may to be to construct a single pipe capable of transporting 1100 m^3 per hour. However, in the short-run, the cheapest solution may be to construct an additional smaller pipe beside the larger pipe, a procedure known as "looping". In addition to this, the short-run solution may be more costly than the long-run solution. Given that the procedure of looping is commonplace in the pipeline industry, the cost curve estimated in this study may represent larger costs than are actually attainable in the long run.

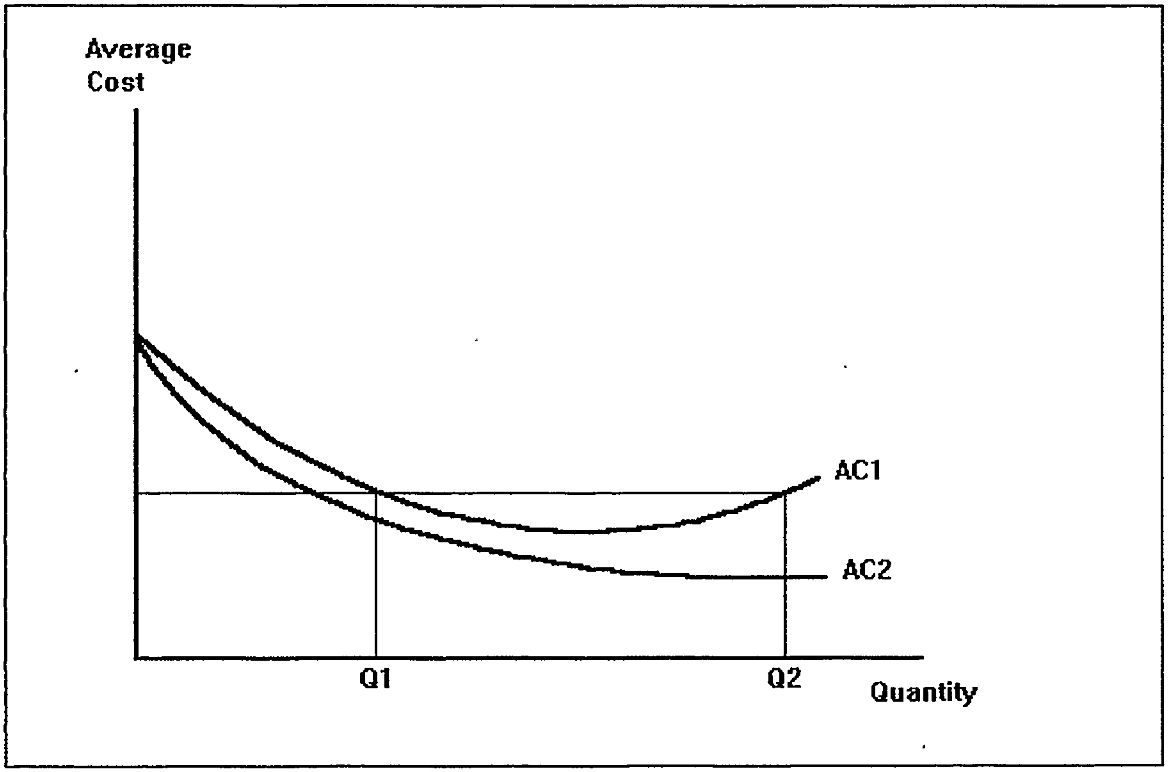

Figure 5.2

A visual representation will enable us to consider the implications of this problem for the subadditivity test. In Figure 5.2 the long run average cost curve represented by the line AC2 assumes that the monopolist employs the most efficient technology at each and every point in time. Meanwhile, the average cost curve, AC1, represents an average cost curve where costs have risen, more than necessary, every time output has expanded (non-optimal short-run adjustments of inputs). Notice that at output level Q2, the cost curve AC2 characterizes a natural monopoly. Further notice that at output level Q2, the average cost curve AC1 may not characterize a natural monopoly. (This will happen if two firms can manufacture in this market jointly producing the monopolists level of output, with both producing more than Q1 level of output.) Therefore, if TCPL has not optimally adjusted its inputs in the short-run we are more likely to find that TCPL is not a natural monopoly. Unfortunately, assessing the natural monopoly status of TCPL by making comparisons across these curves is not possible as the exact position of the long run average cost curve, AC2, is unknown.

For the remainder of this thesis we will be assuming that TCPL has optimally adjusted its inputs in the short-run, and thus that the connection of the short run observations will yield a long-run cost curve. Note that such an assumption is made implicitly in all previous work in this field.

With regard to TCPL and the natural monopoly hypothesis, there are two problems which must be dealt with before we apply econometric methodologies to any TCPL data set. All of TCPL's marginal costs may not be positive. If this is the case, we can infer that the affected markets are too small for TCPL to take full advantage of cost savings which could result from exploiting these markets. Secondly, there is concern over whether we will be estimating a long-run or a short-run cost curve with TCPL data. If we assume that TCPL optimally adjusts its inputs in the short run, then we know that we are estimating a long-run cost curve. However, we must recognize that this assumption may not hold, and in such a case we are more likely to find that TCPL is not a natural monopoly. We now turn our attention to the econometric application of the natural monopoly tests to TCPL, beginning with a discussion of the data which was collected for this study.

5.2 Data Available

TCPL is required to inform the NEB on it's activities quarterly in the "TCPL Quarterly Surveillance Report". Data available from these reports include cost data such as: total operating expenses, depreciation, income taxes, other taxes, labour costs (total labour expenditures, and number of employees), and rate base[1] figures. Throughput data is also available in these reports, disagregated using two methods. Throughput figures are presented as both domestic and international deliveries, and by service type; firm service, interruptible service and temporary winter service. Unfortunately, throughput data is presented only in terms of the amount of natural gas transported and does not reflect the distance that gas was transported. So, the only measure of output available for this study is volumes of transported gas, irrespective of the distance that the gas was moved. In all, the data available from the NEB consist of quarterly data on one input price (labour), quantity of gas transported, total cost of transportation, and a substitute for capital in service[2] (rate base). Unfortunately, after a thorough search of NEB resources in Calgary,

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1 TCPL is currently regulated by the NEB under a regulation scheme known as rate of return regulation. Under this type of regulation, the NEB allows the regulated firm to receive a rate of return on certain costs incurred by the regulated firm. These costs are referred to as the rate base. Note that the rate base is not clearly defined in terms of items which enter into it. The composition of the rate base is usually taken on a per case basis and is the subject of debate in regularly held hearings at the NEB.

2 A standard measure of capital in service is net plant in service. Due to accounting irregularities, a complete data set of this variable was not available. However, net plant is the largest single component of TCPL's rate base. TCPL's rate base seems to be a close approximation to net plant as, for the period of 31/12/89 to 12/31/90, net plant accounted for 99.2% of TCPL's rate base.

Edmonton and Ottawa, and contacting both TCPL and the Canadian Energy Research Institute, only 36 non-continuous observations of the above data (out of a possible 46 observations for the time period 1981 to 1993) could be obtained.

In addition to these figures, supplementary data was collected from Statistics Canada on two more input prices. Interest rate data, in the form of three month averages for the 90 day Prime Corporate rate, and the price of natural gas (cents per cubic metre in terms of total sales in Canada) were acquired. Note that natural gas is an input in the technology of transporting natural gas (TCPL's compressor stations use natural gas as their source of fuel). Additionally, deflator figures in the form of the Consumer Price Index (All Items)[1] were collected from Statistics Canada to be used in eliminating inflation from the cost models in this thesis.

In total, the data set collected for this study consists of 36 non-continuous observations of 3 input prices, operating and maintenence cost data and throughput data not only in aggregate, but disagregated using two methods.

Using this data, it is possible to estimate what Ellig and Giberson refer to as a quasi-long run cost function,

...this estimate employs (the natural log of) operating costs as

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1 The Statistics Canada data may be found in CANSIM. The CPI figures come from series: P484000. The Natural Gas price figures come from series: E13450, and interest rates come from series B14017.

> the dependent variable; operating costs include operation and maintenance costs plus depreciation, amortization, and taxes. This equation is the closest to a long-run cost function that the data permit us to estimate. Strictly speaking, this would be a long-run cost function if pipelines could adjust their capacity instantaneously, and if the depreciation and amortization schedules chosen for accounting purposes accurately reflected economic depreciation and amortization. Because of these complications, we will refer to this equation as the "quasi-long run" cost function (Ellig and Giberson, 1993, pp. 82-83).

In this thesis, we have made the same assumptions as Ellig and Giberson, that TCPL adjust their capital optimally and that depreciation schedules accurately reflect economic depreciation. However, it is unfortunate that the throughput figures do not include a measure of the distance that the gas was transported, as Aivazian et al. (1987) suggest we should have in this line of work.

With regard to the non-continuous nature of the data set; in order to obtain cost function estimates we proceeded with the data at hand by assuming that the observations collected were independent of each other, that is, by assuming that no time-series properties exist within the data set.

This being done, we must recognize the limitation this procedure places upon this study. Because of the discontinuous nature of the data set, we are unable to test for, or correct for, possible autocorrelation in the residuals of the estimated cost models. If autocorrelation is indeed present, and we fail to correct for it, Gujarati informs us of the consequences:

1. The (estimated) residual variance $\hat{\sigma}^2 = \sum e_i^2/(N-k)$ is likely to underestimate the true residual variance, σ^2.
2. As a result, we are likely to overestimate R^2.
3. Even if the true residual variance is not underestimated, $var(\hat{\beta})$ may underestimate $var(\hat{\beta})_{ARI}$ its true variance under (first-order) autocorrelation.
4. Therefore, the usual t and F tests of significance are no longer valid, and if applied, are likely to give seriously misleading conclusions about the statistical significance of the estimated regression coefficients (1988, p.364).

Johnson summarizes these points by stating, " The consequences of applying OLS to a relationship with autocorrelated disturbances are ... unbiased but inefficient estimation and invalid inference procedures (1984, p. 310)." This has two implications for this study. First, with regard to parameter estimates, we can not eliminate any parameters from the models estimated based upon tests of statistical significance. Secondly, the potential inefficiency of parameter estimates generates a problem with regard to the natural monopoly tests. The estimated parameters of the cost models continue to be unbiased, so the tests of natural monopoly will be unbiased. However, as the estimated parameters are potentially inefficient (do not have minimum variance) it is possible that the natural monopoly tests will have inefficient confidence intervals associated with them. With inefficient confidence intervals the likelihood of making a type II error (concluding that there is insignificant evidence to support the natural monopoly hypothesis) increases. Thus, not correcting for possible autocorrelation in the estimated cost models implies that we are more likely to find that TCPL is not a natural monopoly. We now discuss the econometric methodologies applied to this imperfect data set.

5.3 Econometric Methodologies

In this section I disclose the econometric methodologies employed in this study. These include the functional form used in this study, the estimation algorithm used, and the method employed for testing the regularity conditions of a legitimate cost curve.

For this study, the translog functional form was chosen for several reasons. First, this form permits Zellner's iterative methodology to be employed to jointly estimate TCPL's cost curve and two cost share equations, one for labour and one for capital. The cost share equations are derived from the data via the following methodology. Multiplying the rate base figures (as a proxy for physical capital) by the interest rate data, and dividing by total cost yields capital's share of cost. Meanwhile, if we divide employee expenditures by total cost we obtain labour's share of cost. With these cost shares, we can estimate the parameters of the share equations[1] and the cost function by iterating Zellner's two-step procedure. Note that we do not have the required information to estimate a gas input share equation (amount of fuel used in transportation). However, the model estimated has only three inputs: gas, labour and capital, and one of the cost share equations has to be dropped from the analysis in order to obtain a nonsingular covariance matrix. This data limitation has the only effect of determining in advance which cost share equation will be dropped from the analysis, an inconsequential matter as,

> The parameter estimates obtained from iterating Zellner's two-step procedure are asymptotically equivalent to maximum likleyhood estimates and are thus invariant to the equation deleted (Shin and Ying, 1992, p.174).

Additional reasons why the translog form was chosen for this study include: the regularity conditions of a proper cost function are readily tested using this form. Also, this form implies that we begin our analysis with an implicit function, $C = C(y,w)$, a procedure which allows us to estimate a cost function without imposing assumptions regarding TCPL's production technology.

With regard to the econometric estimation of TCPL's cost (using the translog functional form), the following order of estimation and testing was employed. First, the cost functions were estimated using Zellner's two-step

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1 If we apply Shephard's Lemma to the translog cost curve, we can obtain explicit functional forms for the cost share equations (as shown in section 3.2 of this thesis) which we may then estimate.

procedure, then, following Shin and Ying (1992, p. 176), the regularity conditions of homogeneity and symmetry were tested and imposed upon the system. Afterward, non-increasing in factor prices (downward sloping factor demand equations) was evaluated. The own price factor demand elasticities are estimated in this study both at the mean of the data, following Gordon (1990), and at each observation point, following Evans (1983). The method used to obtain these estimates follows Gordon and Rankaduwa (1992, p. 156), that is:

$$\eta_{ii} = S_i + \frac{\gamma_{ii}}{S_i} - 1$$

where γ_{ii} is the coefficient on the second order own price parameters in the translog equation, and S_i is the value of the appropriate cost share equation. Following this test, monotonicity, concavity and increasing in output were evaluated. Following Evans (1983) the points failing regularity condition tests were dropped from further analysis. Once an economically proper cost function[1] was obtained, its econometric properties were assessed. This was preformed using the Durbin Watson test statistic and the Jarque-Bera asymptotic test statistic. These tests are discussed below, respectively.

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1 A proper cost function is one which satisfies homogeneity (which implies negative own price elasticities of input demand equations), symmetry, monotonicity, concavity, and increasing in output.

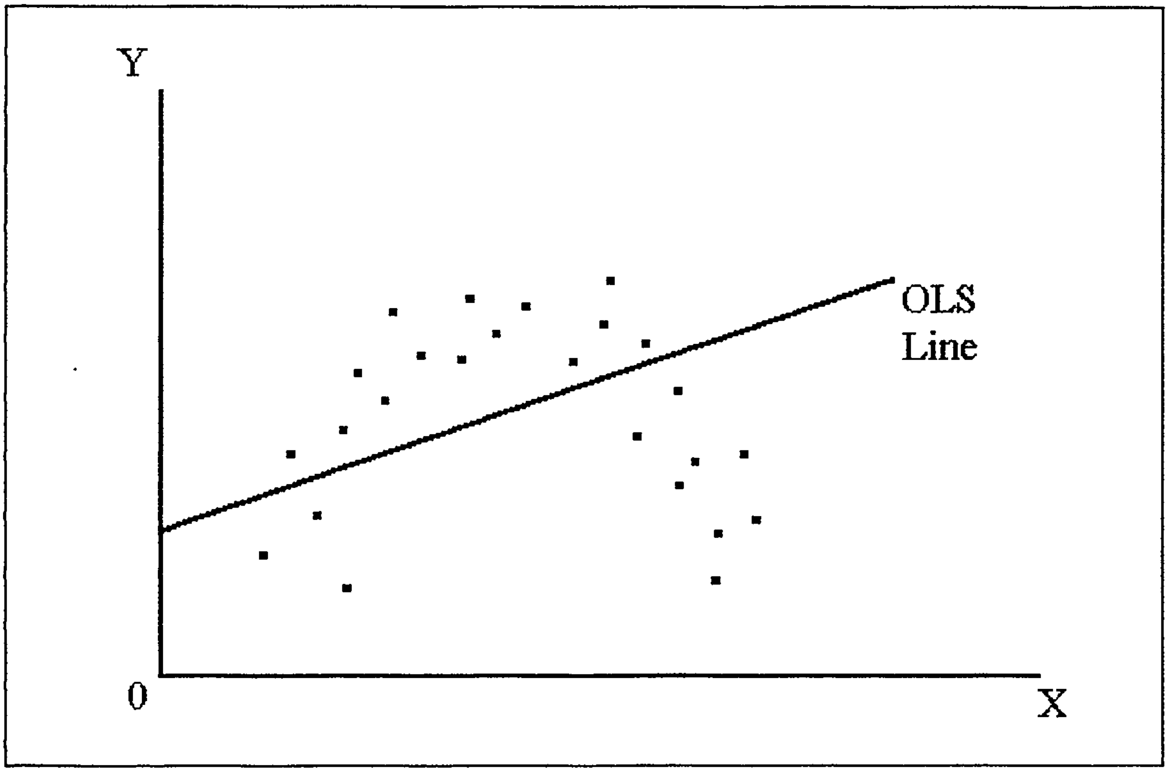

Figure 5.3

The Durbin Watson test statistic was included for the following reason. Given that the data used in this study is non-continuous, we are unable to use the DW statistic to test for first order autocorrelation (Gujarati, 1988, p. 376). However, the Durbin Watson is sensitive to misspecification errors (Gujarati, 1988, p. 409), and can be used as a misspecification test as well as being applied to the more familiar use of autocorrelation detecting. Consider Figure 5.3. We can see that in this case there is a misspecification in the model estimated. A straight line is estimated where a curved one is probably a more appropriate functional form to use. In this case, the Durbin Watson statistic reports a high degree of autocorrelation when the true error is a misspecification error in the order of the estimated function. Given that the translog form is only a second order approximation, and that the data in this application happened to be ordered in terms of increasing total transportation volumes[1], the Durbin Watson test allows us to determine whether or not a higher order approximation is appropriate in the current study.

The Jarque-Bera test statistic is an overall normality test of the OLS residual vector. The functional form of this test is quite involved, and for this reason interested persons are directed to the Shazam User's Reference Manual, Version 7.0, pages 72 and 15 for its explicit construction. However, it is important to note that this test statistic is a member of the family of Lagrange Multiplier test statistics, and as such has a very desirable property in the current application. This property is that (among all three families of maximum likleyhood tests) this family of tests are the most difficult to pass, the test statistic computed by this family is the lowest of all three families. As such, using this test results in the greatest probability of failing to accept the null hypothesis (in this case, normality of residuals). Utilizing this test and failing to reject normality of the regression residuals results in a high degree of confidence in the normality property of the regression residuals.

Following these tests, the natural monopoly tests were preformed using the estimated cost functions (at observations which did not fail any regularity condition tests). We disclose the results of estimation and regularity condition testing in section 5.3.1 below, and the results of the natural monopoly tests in section 5.4.

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1 TCPL's total volumes have steadily increased over the time frame of this study.

5.3.1 Estimation Results

Two multiproduct cost functions were estimated with the available data. One cost function was based upon gas deliveries differentiated on the basis of location of delivery (Canada or U.S.). The other cost function, following Ellig and Giberson (1993), was differentiated on the basis of type of service (firm, interruptible, and temporary winter service). This section discloses cost function parameter estimates and the results of the properness tests which were applied to these two cost functions. First, however, this caveat must be mentioned. Homogeneity and symmetry were tested for and rejected in both multiproduct models. Following Evans (1983, p. 263), Chi squared tests were preformed in both models to test these hypothesis jointly. In the two output model this test generated a test statistic of 108.7 (19 df) compared to a critical value of 30.14, while in the three output model this test generated a test statistic of 161.1 (21 df) compared to a critical value of 32.67. These tests result in the conclusion that homogeneity and symmetry are rejected by the data in both models. Following Evans (1983, p. 263) these restrictions were imposed upon the estimated systems anyway.

The following series of tables (Table 5.1 through Table 5.10) present the two multiproduct cost models estimated, and the results of the normality and legitimacy tests applied to these models. The first cost model presented is the two output model, with transportation differentiated by location of deliveries (Canadian and U.S.). The second cost model presented is the three output model, with transportation differentiated by type of service offered. Each cost model is followed by results of tests of normality, results of the tests of own price elasticity of factor demand equations, monotonicity, strict concavity and concavity respectively. Tests of scale economies (increasing in output) are presented in the following section, 5.4 Tests of Natural Monopoly, as they are not only a regularity condition for a proper cost function, but a test for natural monopoly.

Table 5.1 Parameter Estimates of Two Output Cost Model

VARIABLE[1]	COEFFICIENT	T-RATIO (33 DF)	
CON	19.146	356.1	*
D	-0.114	-1.95	*
W	0.079	24.89	*
W2	0.036	4.05	*
G	0.529	22.32	*
G2	0.024	0.67	
I	0.392	18.72	*
I2	0.003	0.09	
GF	0.201	2.81	*
GF2	0.238	2.54	*
GC	0.086	0.59	
GC2	2.258	1.32	**
GFGC	-0.267	-1.52	**
WGF	-0.005	-1.01	
WG	-0.029	-2.89	*
IG	0.005	0.15	
WGC	0.005	1.01	
WI	-0.007	-1.54	**
IGF	-0.001	-0.03	
IGC	0.001	0.03	
GGF	-0.482	-1.85	*
GGC	0.482	1.85	*

* Significant at the 5% significance level.
** Significant at the 10% significance level.

LOG OF LIKELIHOOD FUNCTION = 193.644
DURBIN-WATSON = 0.7656
JARQUE-BERA ASYMPTOTIC LM NORMALITY TEST
CHI-SQUARE = 0.7598 (2 df)

Own price elasticities evaluated at sample means, (T-statistics, 93 DF)
Wage (Demand for labour): VALUE= -0.467 (-4.08)
Interest (Demand for capital): VALUE= -0.602 (-8.34)
Gas (Demand for inputs): VALUE= -0.426 (-5.56)

1 CON=Constant, D=regulation Dummy variable, W=Wage, W2=Wage squared term, G=Gas price, I=Interest Rate, GF=Foreign deliveries of Gas, GC=Canadian deliveries of Gas.

Table 5.2 Estimates of Own Price Factor Demand Elasticities, T-Ratios (93 D.F.) Presented in Brackets, By Observation, For Two Output Model

Observation	Labour	Capital	Gas
1	-0.469	-0.576	-0.449
	(4.2)	(8.3)	(6.3)
2	-0.500	-0.496	-0.528
	(4.9)	(8.5)	(6.1)
3	-0.456	-0.592	-0.433
	(4.0)	(8.2)	(6.3)
4	-0.491	-0.613	-0.420
	(4.7)	(8.0)	(6.3)
5	-0.514	-0.532	-0.500
	(5.3)	(8.4)	(6.2)
6	-0.474	-0.613	-0.417
	(4.3)	(8.0)	(6.3)
7	-0.497	-0.591	-0.442
	(4.8)	(8.2)	(6.3)
8	-0.582	-0.362	-0.657
	(8.0)	(7.9)	(4.5)
9 *	-0.237	-0.703	-0.302
	(1.350)	(7.0)	(5.6)
10	-0.406	-0.603	-0.414
	(3.1)	(8.1)	(6.3)
11	-0.472	-0.524	-0.497
	(4.3)	(8.5)	(6.2)
12	-0.434	-0.505	-0.507
	(3.6)	(8.5)	(6.2)
13	-0.397	-0.609	-0.407
	(3.0)	(8.0)	(6.2)
14	-0.438	-0.628	-0.395
	(3.6)	(7.9)	(6.2)
15	-0.308	-0.651	-0.358
	(2.0)	(7.6)	(6.0)
16	-0.406	-0.569	-0.362
	(3.1)	(7.5)	(6.0)
17 **	-0.214	-0.743	-0.261
	(1.176)	(6.3)	(5.1)

18 **	-0.220 (1.217)	-0.685 (7.2)	-0.319 (5.7)
19	-0.351 (2.4)	-0.728 (6.6)	-0.288 (5.4)
20	-0.450 (3.8)	-0.707 (6.9)	-0.323 (5.8)
21	-0.460 (4.0)	-0.745 (6.2)	-0.286 (5.4)
22	-0.546 (6.3)	-0.497 (8.5)	-0.539 (6.0)
23	-0.561 (6.9)	-0.363 (7.9)	-0.649 (4.7)
24	-0.572 (7.4)	-0.328 (7.5)	-0.673 (4.1)
25	-0.569 (7.2)	-0.381 (8.0)	-0.639 (4.9)
26	-0.491 (4.7)	-0.401 (8.2)	-0.605 (5.4)
27	-0.466 (4.1)	-0.560 (8.3)	-0.464 (6.3)
28	-0.519 (5.4)	-0.591 (8.2)	-0.447 (6.3)
29	-0.552 (6.5)	-0.566 (8.3)	-0.481 (6.3)
30	-0.417 (3.3)	-0.661 (7.5)	-0.361 (6.0)
31	-0.459 (4.0)	-0.634 (7.8)	-0.394 (6.2)
32	-0.464 (4.1)	-0.676 (7.3)	-0.355 (6.0)
33	-0.469 (4.2)	-0.679 (7.3)	-0.352 (5.9)
34	-0.449 (3.8)	-0.643 (7.7)	-0.383 (6.1)
35	-0.482 (4.5)	-0.608 (8.0)	-0.423 (6.3)
36	-0.495 (4.8)	-0.675 (7.3)	-0.362 (6.0)

* Elasticity is not significant at the 5% confidence level.
** Elasticity is not significant at the 10% confidence level.

Table 5.3 Monotonicity Tests for the Two Output Model.

Observation	C_w	C_i	C_g
1	0.140	0.342	1.163
2	0.128	0.263	1.214
3	0.124	0.325	0.997
4	0.132	0.344	1.223
5	0.118	0.319	0.978
6	0.114	0.509	1.227
7	0.112	0.518	1.394
8	0.114	0.509	1.086
9	0.108	0.493	0.903
10	0.102	0.462	0.912
11	0.102	0.403	1.063
12	0.103	0.367	1.172
13	0.097	0.421	0.999
14	0.086	0.425	0.776
15	0.101	0.459	0.744
16	0.094	0.485	0.785
17	0.094	0.482	0.945
18	0.090	0.390	0.910
19	0.092	0.487	1.130
20	0.077	0.430	0.993
21	0.068	0.455	0.575
22	0.076	0.297	0.514
23	0.062	0.272	0.440
24	0.064	0.256	0.462
25	0.066	0.269	0.478
26	0.071	0.285	0.357
27	0.060	0.329	0.291
28	0.058	0.366	0.271
29	0.059	0.382	0.263
30	0.066	0.430	0.224
31	0.057	0.454	0.156
32	0.059	0.523	0.042
33	0.062	0.531	0.193
34	0.057	0.443	0.170
35	0.054	0.529	0.128
36	0.058	0.639	0.395

Table 5.4 Strict Concavity Test of the Two Output Cost Model.

Observation	C_{ww}	C_{ll}	C_{gg}	D2	D3
1	-0.138	-0.296	-2.078	0.041	-0.081
2	-0.115	-0.175	-1.951	0.020	-0.038
3	-0.108	-0.266	-1.483	0.029	-0.041
4	-0.122	-0.298	-1.664	0.036	-0.058
5	-0.098	-0.256	-1.235	0.025	-0.030
6	-0.091	-0.653	-1.310	0.059	-0.076
7	-0.087	-0.676	-1.503	0.058	-0.087
8	-0.091	-0.654	-1.184	0.059	-0.069
9	-0.082	-0.614	-0.930	0.050	-0.045
10	-0.074	-0.538	-0.884	0.040	-0.034
11	-0.073	-0.410	-1.084	0.030	-0.031
12	-0.074	-0.340	-1.258	0.025	-0.031
13	-0.065	-0.447	-0.994	0.029	-0.028
14	-0.051	-0.457	-0.724	0.023	-0.016
15	-0.072	-0.531	-0.717	0.038	-0.026
16	-0.062	-0.595	-0.793	0.037	-0.028
17	-0.062	-0.587	-0.901	0.036	-0.032
18	-0.057	-0.384	-0.816	0.022	-0.017
19	-0.058	-0.601	-1.100	0.035	-0.038
20	-0.040	-0.470	-1.013	0.019	-0.019
21	-0.032	-0.529	-0.521	0.017	-0.009
22	-0.040	-0.225	-0.561	0.009	-0.005
23	-0.027	-0.188	-0.367	0.005	-0.002
24	-0.028	-0.168	-0.424	0.005	-0.002
25	-0.030	-0.185	-0.469	0.005	-0.002
26	-0.036	-0.206	-0.307	0.007	-0.002
27	-0.025	-0.276	-0.220	0.007	-0.001
28	-0.023	-0.343	-0.218	0.008	-0.002
29	-0.024	-0.374	-0.227	0.009	-0.002
30	-0.030	-0.473	-0.175	0.014	-0.002
31	-0.022	-0.527	-0.106	0.012	-0.001
32	-0.024	-0.700	-0.019	0.017	-0.0001
33	-0.026	-0.724	-0.159	0.019	-0.003
34	-0.022	-0.502	-0.128	0.011	-0.001
35	-0.020	-0.717	-0.084	0.015	-0.001
36	-0.023	-1.045	-0.293	0.024	-0.007

Table 5.5 Concavity Test of the Two Output Cost Model.

Observation	Eigenvalues		
1	-0.131	-0.296	-2.082
2	-0.109	-0.176	-1.954
3	-0.103	-0.266	-1.487
4	-0.116	-0.298	-1.668
5	-0.093	-0.256	-1.238
6	-0.088	-0.652	-1.311
7	-0.085	-0.676	-1.504
8	-0.088	-0.654	-1.186
9	-0.079	-0.614	-0.932
10	-0.071	-0.538	-0.886
11	-0.070	-0.409	-1.086
12	-0.072	-0.340	-1.259
13	-0.063	-0.447	-0.995
14	-0.049	-0.457	-0.725
15	-0.068	-0.531	-0.720
16	-0.060	-0.595	-0.794
17	-0.059	-0.587	-0.902
18	-0.055	-0.384	-0.817
19	-0.057	-0.601	-1.100
20	-0.039	-0.470	-1.013
21	-0.030	-0.519	-0.531
22	-0.037	-0.224	-0.562
23	-0.025	-0.188	-0.367
24	-0.026	-0.167	-0.425
25	-0.028	-0.185	-0.470
26	-0.033	-0.206	-0.309
27	-0.023	-0.221	-0.276
28	-0.021	-0.219	-0.342
29	-0.022	-0.228	-0.375
30	-0.027	-0.177	-0.472
31	-0.019	-0.108	-0.526
32	-0.004	-0.039	-0.701
33	-0.023	-0.161	-0.723
34	-0.019	-0.130	-0.502
35	-0.017	-0.086	-0.717
36	-0.022	-0.293	-1.044

Table 5.6 Estimated Parameters of the Three Output Cost Model.

VARIABLE[1]	COEFFICIENT	T-RATIO (33 DF)	
CON	19.132	364.2	*
D	-0.081	-1.81	*
W	0.078	26.37	*
W2	0.031	5.11	*
G	0.537	23.49	*
G2	0.071	2.78	*
I	0.384	18.88	*
I2	0.042	1.85	*
A	0.003	0.22	
A2	-0.002	-1.48	**
F	0.445	5.9	*
F2	1.293	4.89	*
N	-0.074	-1.19	
N2	-0.022	-1.29	
FN	-0.337	-2.88	*
FA	-0.008	-0.52	
NA	-0.015	-0.68	
WF	0.001	0.25	
WN	0.001	0.35	
WA	-0.001	-2.16	*
IF	0.008	0.48	
IN	0.000	-0.03	
IA	-0.008	-1.69	**
GF	-0.867	-3.59	*
GN	0.861	3.59	*
GA	0.006	0.28	
WG	-0.030	-4.09	*
WI	-0.001	-0.18	
IG	-0.041	-1.73	*

* Significant at the 5% significance level.
** Significant at the 10% significance level.

LOG OF LIKELIHOOD FUNCTION = 210.697
DURBIN-WATSON = 1.228
JARQUE-BERA ASYMPTOTIC LM NORMALITY TEST
CHI-SQUARE = 5.2254 WITH 2 DEGREES OF FREEDOM

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1 Con=Constant, D=regulation Dummy variable, W=Wage, W2=Wage squared term, G=Gas price, I=Interest rate, F=Firm service deliveries, N=Interruptible deliveries, A=Firm service tendered.

Own price elasticities evaluated at sample means (T-statistics, 86 DF).

Wage:	VALUE= -0.531 (-6.92)
Interest:	VALUE= -0.331 (-5.95)
Gas:	VALUE= -0.507 (-9.01)

Table 5.7 Estimates of Own Price Factor Demand Elasticities, T-Ratios (83 D.F.) Presented in Brackets, By Observation, for the Three Output Cost Model.

Observation	Labour	Capital	Gas
1	-0.534	-0.483	-0.356
	(7.1)	(8.9)	(7.0)
2	-0.560	-0.418	-0.415
	(8.1)	(9.2)	(6.7)
3	-0.524	-0.495	-0.343
	(6.7)	(8.8)	(7.0)
4	-0.552	-0.510	-0.333
	(7.8)	(8.6)	(7.0)
5	-0.572	-0.448	-0.395
	(8.6)	(9.2)	(6.9)
6	-0.509	-0.521	-0.312
	(7.2)	(8.6)	(7.0)
7	-0.557	-0.494	-0.350
	(8.0)	(8.8)	(7.0)
8	-0.625	-0.301	-0.466
	(12.6)	(8.5)	(4.5)
9	-0.341	-0.568	-0.231
	(2.9)	(7.3)	(6.0)
10	-0.482	-0.503	-0.328
	(5.5)	(8.7)	(7.0)
11	-0.537	-0.441	-0.393
	(7.2)	(9.2)	(6.9)
12	-0.505	-0.426	-0.400

	(6.1)	(9.2)	(6.9)
13	-0.475	-0.508	-0.322
	(5.3)	(8.7)	(7.0)
14	-0.509	-0.521	-0.312
	(6.2)	(8.4)	(6.9)
15	-0.400	-0.537	-0.280
	(3.8)	(8.1)	(6.6)
16	-0.483	-0.542	-0.283
	(5.5)	(8.0)	(6.7)
17	-0.321	-0.585	-0.194
	(2.6)	(6.4)	(5.4)
18	-0.326	-0.558	-0.246
	(2.6)	(7.6)	(6.2)
19	-0.436	-0.579	-0.219
	(4.4)	(6.7)	(5.8)
20	-0.519	-0.569	-0.249
	(6.5)	(7.2)	(6.3)
21	-0.527	-0.585	-0.217
	(6.8)	(6.3)	(5.8)
22	-0.597	-0.419	-0.422
	(10.1)	(9.2)	(6.6)
23	-0.609	-0.302	-0.467
	(11.0)	(8.5)	(4.8)
24	-0.617	-0.269	-0.456
	(11.7)	(8.0)	(3.9)
25	-0.615	-0.318	-0.467
	(11.6)	(8.7)	(5.0)
26	-0.553	-0.335	-0.458
	(7.8)	(8.8)	(5.8)
27	-0.532	-0.368	-0.470
	(7.0)	(7.0)	(9.1)

28	-0.575	-0.494	-0.354
	(8.8)	(8.8)	(7.0)
29	-0.602	-0.475	-0.381
	(10.5)	(9.0)	(7.0)
30	-0.492	-0.543	-0.283
	(5.7)	(8.0)	(6.6)
31	-0.526	-0.525	-0.311
	(6.8)	(8.4)	(6.9)
32	-0.530	-0.552	-0.278
	(7.0)	(7.8)	(6.6)
33	-0.534	-0.554	-0.275
	(7.1)	(7.7)	(6.6)
34	-0.518	-0.531	-0.302
	(6.4)	(8.2)	(6.8)
35	-0.545	-0.507	-0.334
	(7.5)	(8.7)	(7.0)
36	-0.556	-0.552	-0.284
	(7.9)	(7.8)	(6.7)

Table 5.8 Test for Monotonicity in the Three Output Cost Model.

Observation	C_w	C_i	C_q
1	0.145	0.354	1.554
2	0.135	0.281	1.122
3	0.128	0.332	0.937
4	0.137	0.355	1.332
5	0.159	0.414	1.075
6	0.109	0.507	0.632
7	0.110	0.540	0.691
8	0.113	0.503	1.983
9	0.102	0.465	0.816
10	0.089	0.444	-5.010
11	0.106	0.430	1.021
12	0.101	0.371	1.025
13	0.089	0.400	0.851
14	0.081	0.402	0.707
15	0.130	0.566	0.770
16	0.091	0.468	0.736
17	0.084	0.443	0.784
18	0.083	0.368	0.731
19	0.083	0.461	0.978
20	0.073	0.425	0.560
21	0.065	0.428	0.937
22	0.096	0.390	0.369
23	0.063	0.275	0.332
24	0.066	0.272	0.203
25	0.071	0.301	0.363
26	0.075	0.293	0.237
27	0.061	0.329	0.175
28	0.063	0.397	0.273
29	0.062	0.402	-0.102
30	0.066	0.416	0.221
31	0.056	0.425	0.081
32	0.060	0.495	0.569
33	0.061	0.510	0.192
34	0.056	0.425	0.193
35	0.054	0.496	0.149
36	0.054	0.582	0.016

Table 5.9 Tests for Strict Concavity in the Three Output Cost Model.

Observation	C_{ww}	C_{ll}	C_{qq}	D2	D3
1	-0.166	-0.277	-2.639	0.046	-0.118
2	-0.143	-0.169	-1.669	0.024	-0.039
3	-0.130	-0.246	-1.279	0.032	-0.039
4	-0.151	-0.278	-1.724	0.042	-0.071
5	-0.187	-0.307	-1.282	0.058	-0.072
6	-0.096	-0.585	-0.604	0.056	-0.032
7	-0.094	-0.638	-0.674	0.061	-0.039
8	-0.102	-0.581	-2.126	0.059	-0.124
9	-0.085	-0.516	-0.784	0.044	-0.033
10	-0.065	-0.463	5.064	0.030	0.154
11	-0.088	-0.396	-0.989	0.035	-0.034
12	-0.079	-0.309	-1.039	0.025	-0.025
13	-0.064	-0.380	-0.793	0.025	-0.019
14	-0.051	-0.386	-0.613	0.020	-0.012
15	-0.127	-0.603	-0.697	0.077	-0.052
16	-0.066	-0.514	-0.690	0.034	-0.023
17	-0.057	-0.480	-0.698	0.028	-0.019
18	-0.056	-0.324	-0.612	0.018	-0.011
19	-0.054	-0.508	-0.902	0.028	-0.024
20	-0.040	-0.417	-0.508	0.017	-0.008
21	-0.032	-0.444	-0.820	0.014	-0.011
22	-0.062	-0.272	-0.331	0.017	-0.005
23	-0.030	-0.171	-0.236	0.005	-0.001
24	-0.032	-0.161	-0.130	0.005	-0.001
25	-0.037	-0.188	-0.300	0.007	-0.002
26	-0.044	-0.191	-0.157	0.009	-0.001
27	-0.028	-0.248	-0.095	0.007	-0.001
28	-0.029	-0.337	-0.184	0.010	-0.002
29	-0.028	-0.355	0.159	0.010	0.002
30	-0.034	-0.409	-0.138	0.014	-0.002
31	-0.024	-0.440	-0.020	0.011	0.000
32	-0.027	-0.592	-0.427	0.016	-0.007
33	-0.028	-0.621	-0.117	0.018	-0.002
34	-0.024	-0.431	-0.112	0.010	-0.001
35	-0.022	-0.599	-0.072	0.013	-0.001
36	-0.022	-0.846	0.030	0.019	0.001

Table 5.10 Tests for Concavity in the Three Output Cost Model.

Observation	Eigenvalues		
1	-0.161	-0.275	-2.646
2	-0.138	-0.168	-1.675
3	-0.124	-0.243	-1.287
4	-0.147	-0.276	-1.730
5	-0.182	-0.305	-1.289
6	-0.091	-0.539	-0.656
7	-0.091	-0.596	-0.720
8	-0.100	-0.578	-2.130
9	-0.082	-0.506	-0.798
10	5.066	-0.065	-0.463
11	-0.086	-0.392	-0.994
12	-0.077	-0.307	-1.044
13	-0.062	-0.375	-0.799
14	-0.050	-0.379	-0.622
15	-0.124	-0.583	-0.720
16	-0.063	-0.500	-0.707
17	-0.055	-0.470	-0.711
18	-0.053	-0.319	-0.618
19	-0.053	-0.501	-0.910
20	-0.038	-0.397	-0.530
21	-0.031	-0.439	-0.826
22	-0.058	-0.256	-0.351
23	-0.028	-0.163	-0.246
24	-0.028	-0.119	-0.176
25	-0.034	-0.181	-0.309
26	-0.038	-0.147	-0.207
27	-0.023	-0.095	-0.253
28	-0.027	-0.179	-0.344
29	0.164	-0.030	-0.358
30	-0.030	-0.137	-0.414
31	-0.004	-0.036	-0.443
32	-0.027	-0.416	-0.605
33	-0.024	-0.116	-0.626
34	-0.020	-0.111	-0.435
35	-0.017	-0.073	-0.603
36	0.307	-0.026	-0.849

5.3.2 Summary of Normality and Properness Tests

The two output model, with outputs differentiated by location of deliveries, shows all data points to be regular and proper: symmetric, homogeneous, concave, monotonic, and increasing in output (see table 5.11 in section 5.4). Further, this estimated cost curve yields factor demand equations which are downward sloping at all observed data points, as well as at the mean of the data. The Durbin Watson test result suggests no evidence of misspecification of the order of the model and the Jarque-Bera test shows no evidence to reject normality of the regression residuals.

In the three output, differentiated by type of delivery model, all observed data points are homogeneous, symmetric, increasing in output (see table 5.12 in section 5.4) and yield downward sloping factor demand equations. However, observations 10 and 29 are neither monotonic nor concave while observation 36 is not concave. As with the two output model, the Durbin Watson test result suggests no evidence of misspecification of the order of the model and the Jarque-Bera test shows no evidence to reject normality of the regression residuals. In this model, 92% of the observations are regular and proper, and observations failing any regularity condition test are dropped from the natural monopoly analysis.

In addition to these tests, another test of the specification of both models was performed. The Cobb-Douglas functional form was estimated and tested against the translog specifications using a likelihood ratio test procedure. In the two output model, this specification test generated a test statistic of 1717.8 distributed as Chi squared (15 df) compared to a critical value of 24.996. In the three output model, this same test yielded a statistic of 1748.1 (21 df) compared to a critical value of 32.67. These results allow us to reject the Cobb-Douglas specification of the cost models. Unfortunately, we are not able to test the specification of the translog cost models by deleting insignificant variables from either model due to possible autocorrelation (undetectable in this case due to the discontinuous nature of the data set) in the residuals of these models.

5.4 Tests for Natural Monopoly

With proper cost functions, it now becomes possible to perform tests for natural monopoly. Two tests were conducted to determine the natural monopoly status of TCPL. Panzar's (1989) test of necessary and sufficient conditions and Evans' (1983) test of subadditivity. Both of these tests were applied to both estimated cost equations and results of these tests follow, though a complete discussion of these results must wait until the next section.

Panzar's necessary and sufficient condition test involves a two step procedure. First, we assess the scale economies of TCPL, and then test for the presence of transray convexity. The following section discloses the tests performed for scale economies and transray convexity respectively.

The formula used to evaluate economies of scale in this thesis is presented in Chapter Two, and is presented here, for clearness of exposition.

$$S = \frac{C(y,w)}{\Sigma y_i C_i}$$

If we find S > 1, then we can conclude that TCPL encounters economies of scale, and strictly decreasing ray average costs, which is required for one of the sufficient conditions for natural monopoly disclosed in Chapter Two. Notice that in order to perform this test, marginal cost must be estimated first. This test is performed using both the two and three output cost models, results of this test are presented below in tables 5.11 and 5.12.

Table 5.11 Marginal Cost and Scale Economies in the Two Output Cost Model.

Observation Number	C_f	C_c	Scale Economies
1	-6.66e-04	2.97e-03	1.05
2	-9.99e-04	3.33e-03	1.07
3	-7.13e-04	2.90e-03	1.06
4	-1.35e-03	3.11e-03	1.07
5	-1.16e-03	3.49e-03	1.08
6	-2.90e-03	3.44e-03	1.08
7	-4.76e-03	3.98e-03	1.10
8	-2.23e-03	3.76e-03	1.07
9	-1.25e-03	2.83e-03	1.08
10	-1.58e-03	3.02e-03	1.07
11	-2.34e-03	3.50e-03	1.09
12	-2.54e-03	3.43e-03	1.09
13	-1.69e-03	2.79e-03	1.07
14	-1.26e-03	3.01e-03	1.08
15	-1.27e-03	3.55e-03	1.11
16	-1.27e-03	3.49e-03	1.10
17	-1.56e-03	2.65e-03	1.08
18	-1.93e-03	3.02e-03	1.10
19	-3.22e-03	3.56e-03	1.11
20	-2.22e-03	3.74e-03	1.12
21	-6.65e-04	2.50e-03	1.08
22	-5.40e-04	3.11e-03	1.09
23	-5.35e-04	2.55e-03	1.06
24	-5.43e-04	2.78e-03	1.08
25	-5.29e-04	2.85e-03	1.08

26	-4.05e-04	2.58e-03	1.07
27	-3.88e-04	2.54e-03	1.08
28	-3.77e-04	2.77e-03	1.10
29	-3.84e-04	3.06e-03	1.10
30	-3.03e-04	2.55e-03	1.09
31	-2.76e-04	2.55e-03	1.09
32	-2.93e-04	3.83e-03	1.15
33	-2.66e-04	2.55e-03	1.09
34	-2.44e-04	2.34e-03	1.09
35	-2.38e-04	2.38e-03	1.09
36	-5.37e-04	2.44e-03	1.09

Note: C_f is foreign delivery marginal cost, C_c is Canadian delivery marginal cost.

Table 5.12 Marginal Cost and Scale Economies in the Three Output Cost Model.

Observation	C_f	C_n	C_a	Scale Economies
1	1.18e-03	-9.18e-04	-4.85e-04	3.21
2	1.29e-03	-1.09e-03	-1.41e-03	3.21
3	1.09e-03	-1.02e-03	-5.12e-04	3.17
4	1.26e-03	-7.34e-04	-2.60e-03	3.29
5	1.35e-03	-6.34e-04	-1272.38	3.10
6	1.34e-03	-9.63e-04	-1.10e-02	3.19
7	1.58e-03	-9.68e-04	-0.13408	3.23
8	1.84e-03	-3.34e-04	-1.10e-02	3.61
9	1.09e-03	-7.03e-04	-5.87e-04	3.29
11	1.41e-03	-5.78e-04	-0.14443	3.32
12	1.39e-03	-6.78e-04	-4.24e-03	3.35
13	1.12e-03	-6.47e-04	-4.60e-04	3.29
14	1.13e-03	-6.90e-04	-4.93e-04	3.28
15	1.30e-03	-5.18e-04	-1219.34	3.14
16	1.26e-03	-8.03e-04	-1.75e-03	3.28
17	1.09e-03	-6.50e-04	-2.28e-04	3.34
18	1.20e-03	-6.51e-04	-4.45e-04	3.37
19	1.46e-03	-6.39e-04	-1.10e-03	3.47
20	1.40e-03	-1.02e-03	-2.56e-03	3.32
21	9.30e-04	-4.43e-04	-4.06e-04	3.33
22	9.89e-04	-7.84e-04	-1279.58	2.96

23	8.03e-04	-7.04e-04	-1.21e-03	3.07
24	8.58e-04	-9.19e-04	-5.58e-03	3.04
25	8.90e-04	-8.01e-04	-7.62e-02	3.06
26	7.56e-04	-7.89e-04	-2.46e-03	3.02
27	7.23e-04	-7.35e-04	-2.09e-03	3.05
28	7.71e-04	-6.63e-04	-0.1502	3.04
30	6.85e-04	-7.24e-04	-1.11e-03	3.06
31	6.50e-04	-7.71e-04	-5.10e-04	3.03
32	6.25e-04	-4.21e-04	-1.12e-03	3.14
33	6.62e-04	-7.86e-04	-1.19e-03	3.05
34	6.03e-04	-6.77e-04	-7.06e-04	3.05
35	5.87e-04	-6.38e-04	-1.01e-03	3.01

Note: C_f is firm service marginal cost, C_n is interruptible service, and C_a is temporary winter service marginal cost.

These models show evidence for economies of scale, and decreasing ray average costs, which is necessary for two sufficient conditions for natural monopoly. However, the presence of negative marginal costs must be noted. As stated in section 5.1, negative marginal costs should be interpreted as saying that TCPL's markets are too small for TCPL to take full advantage of cost savings obtainable from exploiting these markets. It is consistent with this reasoning that we find negative marginal costs only in TCPL's smaller markets, and not in TCPL's larger markets.

Note that all estimates for the three output model exceed the upper limit presented by Aivazian et al. (1987) of 2.07. A plausible explanation for this result exists, as discussed in Chapter Four. Recall that the upper limit of scale economies of 2.07, which Aivazian et. al. refer to, was presented in an engineering study dated in 1972[1]. It is possible that more efficient compressor

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1 Aivazian et. al. 1987 quotes Robinson, S. T., "Powering of Natural Gas Pipelines," Journal of Engineering for Power, A.S.M.E. Transactions (continued...)

technologies exist within the data set used in this study than existed in 1972. These more efficient compressor technologies could raise the upper limit of scale economies obtainable in natural gas pipelines. To test the reliability of the high estimates of scale economies in the three output model, a single output translog cost function was considered.

We first tested the legitimacy of estimating a single output cost function. Fortunately, applying Evans' (1983, p. 256) test of separability of inputs and outputs (presented in Chapter Three of this work) to the three output model yields a test statistic of 1.1499 (distributed as an F statistic with 6 and 86 df) compared to a critical value of 3.71 (5% significance level). With this result, we fail to reject the separability hypothesis, and as Evans states:

> If these restrictions are accepted, it may be possible to form an aggregate output measure, estimate a single-product cost function, and use scale-economy estimates to test whether there is a natural monopoly (1983, p. 256).

Thus we may legitimately estimate a single output cost function with the available data.

Applying simple addition to the output measures in the three output model yields an aggregate output measure of delivered gas. This single output cost model was estimated using the translog flexible functional form,

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1(...continued)
94 (July 1972), 181-186 to obtain the upper limit of scale economies of 2.07.

restricted for homogeneity[1] and symmetry. Parameter estimates of this cost function are presented in table 5.13 below.

Table 5.13 Parameter Estimates for the Single Output Model.

LOG OF THE LIKELIHOOD FUNCTION = 193.98

Variable	Coefficient	T-Ratio (37 DF)	
CON	19.15	413.3	*
D	-0.16972	-4.051	*
W	0.08017	27.55	*
W2	0.02855	4.864	*
G	0.52696	23.91	*
G2	0.59924	0.0021	
I	0.39286	20.16	*
I2	-0.01201	-0.4915	
OUT	0.30735	4.646	*
OUT2	0.79095	2.425	*
WI	-0.00829	-2.212	*
IG	0.02025	0.7788	
WG	-0.02031	-2.839	*

* Significant at the 5% level.

DURBIN-WATSON = 2.0872
JARQUE-BERA ASYMPTOTIC LM NORMALITY TEST
CHI-SQUARE = 0.6156 WITH 2 DEGREES OF FREEDOM

This model was used to test for economies of scale. Recall that in the single output case, economies of scale reduces to Scale=AC/MC. Results of this test are presented in table 5.14.

1 Note that homogeneity in a single output setting implies that all output/price cross terms in the translog flexible functional form be restricted to zero.

Table 5.14 Marginal Cost and Scale Economies, Single Output Cost Model.

Observation	MC	Scale
1	8.96e-04	2.48
2	1.04e-03	2.53
3	8.77e-04	2.50
4	1.01e-03	2.54
5	1.09e-03	2.55
6	1.17e-03	2.58
7	1.38e-03	2.63
8	1.24e-03	2.55
9	9.08e-04	2.57
10	9.70e-04	2.55
11	1.17e-03	2.60
12	1.15e-03	2.61
13	9.21e-04	2.55
14	9.50e-04	2.57
15	1.09e-03	2.61
16	1.08e-03	2.60
17	8.72e-04	2.58
18	9.99e-04	2.62
19	1.21e-03	2.67
20	1.23e-03	2.68
21	7.47e-04	2.53
22	8.53e-04	2.53
23	7.17e-04	2.49
24	7.72e-04	2.51
25	7.85e-04	2.52
26	6.80e-04	2.48
27	6.61e-04	2.51
28	6.94e-04	2.52
29	7.52e-04	2.53
30	6.17e-04	2.50
31	5.92e-04	2.49
32	5.42e-04	2.47
33	5.94e-04	2.50
34	5.42e-04	2.49
35	5.37e-04	2.47
36	5.52e-04	2.48

These results confirm the seemingly high estimates of scale economies obtained from the three output cost model.

As a result of this investigation we find economies of scale in each model estimated above. Unusually high estimates of scale economies in one multiproduct model are confirmed in the single output model. These results confirm the first of Panzar's tests of the necessary and sufficient conditions for a natural monopoly (that of scale economies, and by analogy strictly decreasing ray average costs).

With the economies of scale test behind us, we now turn our attention to the second part of Panzar's test, the test for transray convexity.

Recall from Chapter Three that, according to Squires (1988), transray convexity exists if it exists between product pairs. Further it exists if the cost curve is convex in outputs (second order own partial derivatives with respect to outputs are positive) and cost complementarities (negative cross partial derivatives, or economies of scope) exist. Squires also presents another set of conditions for transray convexity to hold, but this is all that we will need in the following section.

I now draw your attention to the fact that nested in the transray convexity test are other tests of natural monopoly. These are the tests of cost complementarities (by itself a sufficient condition for natural monopoly) and economies of scope (a necessary condition for natural monopoly). Therefore, Squires (1988) test of transray convexity allows us to test for the presence of cost complementarities and economies of scope as well.

In order to perform this test of transray convexity, partial derivatives of the estimated cost functions were evaluated at all observed data points. Results of this test follow in tables 5.15 and 5.16. For accuracy of notation, in the two output cost model the partial derivatives are as follows: C_{cc} is the second order own partial derivative with respect to Canadian deliveries, C_{ff} is the second order own partial derivative with respect to foreign deliveries and C_{cf} is the second order cross partial derivative. Recall that transray convexity requires $C_{cc} > 0$, $C_{ff} > 0$ and $C_{cf} < 0$, while cost complementarities requires only that $C_{cf} < 0$.

Table 5.15 Transray Convexity Tests for the Two Output Cost Model.

Observation	C_{ff}	C_{cc}	C_{cf}
1	3.90e-07	-1.64e-06	-2.10e-08
2	8.08e-07	-2.03e-06	-3.31e-08
3	4.13e-07	-1.55e-06	-2.02e-08
4	1.31e-06	-1.75e-06	-3.70e-08
5	1.00e-06	-2.20e-06	-3.72e-08
6	5.18e-06	-2.08e-06	-7.61e-08
7	1.34e-05	-2.74e-06	-1.41e-07
8	3.24e-06	-2.49e-06	-6.84e-08
9	1.03e-06	-1.44e-06	-2.84e-08
10	1.59e-06	-1.63e-06	-3.71e-08
11	3.44e-06	-2.16e-06	-6.39e-08
12	4.06e-06	-2.08e-06	-6.78e-08
13	1.78e-06	-1.39e-06	-3.56e-08
14	1.02e-06	-1.62e-06	-2.99e-08
15	1.09e-06	-2.24e-06	-3.78e-08
16	1.10e-06	-2.17e-06	-3.74e-08
17	1.52e-06	-1.25e-06	-3.09e-08
18	2.26e-06	-1.62e-06	-4.32e-08

19	6.16e-06	-2.21e-06	-8.48e-08
20	3.13e-06	-2.46e-06	-6.61e-08
21	3.02e-07	-1.14e-06	-1.36e-08
22	2.27e-07	-1.77e-06	-1.60e-08
23	1.98e-07	-1.19e-06	-1.13e-08
24	2.13e-07	-1.41e-06	-1.32e-08
25	2.08e-07	-1.48e-06	-1.35e-08
26	1.20e-07	-1.23e-06	-9.18e-09
27	1.07e-07	-1.18e-06	-8.37e-09
28	1.05e-07	-1.41e-06	-9.31e-09
29	1.14e-07	-1.71e-06	-1.10e-08
30	6.87e-08	-1.20e-06	-6.91e-09
31	5.58e-08	-1.20e-06	-6.17e-09
32	6.98e-08	-2.67e-06	-1.14e-08
33	5.54e-08	-1.20e-06	-6.32e-09
34	4.53e-08	-1.02e-06	-5.14e-09
35	4.17e-08	-1.05e-06	-4.97e-09
36	1.91e-07	-1.08e-06	-1.04e-08

For the three output model, C_{ff}, C_{nn}, and C_{aa} represent the second order own partial derivatives for firm service, interruptible service, and temporary winter service respectively. C_{fn}, C_{fa}, and C_{na} represent the cross partial derivatives. As in the two output model, transray convexity requires all second order own partial derivatives be positive, and all second order cross partial derivatives be negative while cost complimentarities requires only the latter hold true.

Table 5.16 Transray Convexity Tests for the Three Output Cost Model.

Obs	C_{ff}	C_{aa}	C_{nn}	C_{fn}	C_{fa}	C_{na}
1	-1.54e-07	1.40e-06	5.44e-07	-3.21e-08	-3.75e-09	-2.65e-08
2	-1.87e-07	1.23e-05	8.55e-07	-4.72e-08	-1.26e-08	-1.06e-07
3	-1.32e-07	1.59e-06	7.32e-07	-3.61e-08	-3.72e-09	-3.47e-08
4	-1.85e-07	4.21e-05	4.35e-07	-3.65e-08	-2.37e-08	-1.49e-07
5	-2.10e-07	1.24e+07	4.21e-07	-4.38e-08	-1.53e-02	-0.10248

6	-2.10e-07	8.33e-04	9.61e-07	-6.65e-08	-1.20e-07	-1.18e-06
7	-3.00e-07	0.131951	1.08e-06	-9.09e-08	-1.89e-06	-1.73e-05
8	-4.41e-07	7.72e-04	1.31e-07	-4.14e-08	-1.76e-07	-4.33e-07
9	-1.38e-07	2.16e-06	4.63e-07	-3.52e-08	-4.68e-09	-3.78e-08
11	-2.40e-07	0.142295	3.86e-07	-4.89e-08	-1.71e-06	-1.03e-05
12	-2.32e-07	1.16e-04	4.74e-07	-4.99e-08	-4.64e-08	-3.00e-07
13	-1.48e-07	1.31e-06	4.08e-07	-3.53e-08	-3.77e-09	-2.80e-08
14	-1.50e-07	1.52e-06	4.92e-07	-4.04e-08	-4.14e-09	-3.45e-08
15	-1.99e-07	1.19e+07	3.71e-07	-4.71e-08	-1.51e-02	-0.11134
16	-1.87e-07	2.01e-05	6.61e-07	-5.20e-08	-1.72e-08	-1.47e-07
17	-1.40e-07	3.21e-07	4.19e-07	-3.50e-08	-1.81e-09	-1.42e-08
18	-1.71e-07	1.25e-06	4.69e-07	-4.41e-08	-4.05e-09	-3.16e-08
19	-2.62e-07	7.92e-06	4.66e-07	-5.64e-08	-1.31e-08	-8.19e-08
20	-2.31e-07	4.43e-05	1.11e-06	-7.72e-08	-2.89e-08	-2.96e-07
21	-1.01e-07	9.75e-07	1.90e-07	-1.97e-08	-2.62e-09	-1.60e-08
22	-1.08e-07	1.25e+07	6.35e-07	-3.69e-08	-1.05e-02	-0.12491
23	-7.24e-08	8.93e-06	4.91e-07	-2.63e-08	-6.59e-09	-8.02e-08
24	-8.17e-08	1.97e-04	8.05e-07	-3.48e-08	-3.32e-08	-4.82e-07
25	-8.81e-08	3.76e-02	6.07e-07	-3.13e-08	-4.83e-07	-5.83e-06
26	-6.30e-08	3.74e-05	5.84e-07	-2.57e-08	-1.25e-08	-1.75e-07
27	-5.80e-08	2.72e-05	5.54e-07	-2.53e-08	-1.03e-08	-1.53e-07
28	-6.61e-08	0.148067	4.62e-07	-2.49e-08	-8.36e-07	-1.07e-05
30	-5.15e-08	7.64e-06	4.95e-07	-2.14e-08	-5.08e-09	-7.31e-08
31	-4.63e-08	1.61e-06	6.03e-07	-2.32e-08	-2.22e-09	-3.85e-08
32	-4.34e-08	7.38e-06	1.65e-07	-1.13e-08	-4.52e-09	-4.01e-08
33	-4.75e-08	8.78e-06	5.41e-07	-2.04e-08	-5.19e-09	-7.89e-08
34	-3.94e-08	2.99e-06	4.15e-07	-1.65e-08	-2.72e-09	-4.04e-08
35	-3.76e-08	6.22e-06	4.02e-07	-1.67e-08	-3.88e-09	-6.07e-08

The transray convexity test fails in both multiple output cost models. We fail to find cost convexity for all products in both models, however, we do find evidence for cost complementarities in both models. An analysis of this finding will be presented in section 5.5, but for now we continue presenting natural monopoly test results.

The Evans (1983) subadditivity test was next applied to the two output and three output models. Recall that this is measured by the formula presented in Chapter Two, reproduced here;

$$Sub_t = \frac{C - (C_a + C_b)}{C}$$

In this formula, C is the cost of the monopolist at each output level while C_a and C_b represent the costs of the two firms (which jointly produce the output of the monopolist). If Sub_t is negative then the cost of producing the monopolists output is greater if it is produced by two firms than if it is produced by one. Such a result would allow us to conclude that TCPL is a natural monopoly.

Recall (from Chapter Three) that the region of the subadditivity test should be restricted by the following two notions:

1) Neither hypothetical firm should be allowed to produce less of any output than we have observed the monopolist produce,
2) Neither hypothetical firm should be allowed to specialize in any output to an extent greater than the monopolist has.

These restrictions define an allowable region under which the subadditivity test can be preformed. In this analysis, this region was split up between the two hypothetical firms as follows: if one hypothetical firm produced 10% of the allowed output then the other firm was restricted to produce the remaining 90%. Further, a grid search pattern was employed in this analysis to examine the entire allowable output region that exists. The following search pattern was employed in this test: one firm was chosen and allowed to produce 0%, 10%, 20% ... 90% of the allowed output for each product produced. The other firm produced the remainder. In the two output case, the resulting test statistics forms a matrix under which the rows, and columns, of the matrix represent subadditivity tests obtained from varying the distribution of one output while holding the distribution of the other output constant. In the three output case, this grid search pattern yields ten such matrices (in each matrix the output mix between the two firms of the third output is held constant). Finally note that as this test is a linear one, it is a rather straightforward (and intensive) procedure to use standard testing algorithms to obtain the necessary predictions, and confidence intervals, for this test.

This test was applied to the two output model for the most recent observations, 30 to 36 inclusive, and to the three output model for the observations 30 to 35 inclusive, observation 36 being dropped from this analysis due to failing the concavity test. The complete results of these tests comprises some 45 pages and as such are not included in this work. However, the results are consistent and as such we can present a portion, and summary, of them here without loss of generality.

The subadditivity test results, with T-ratios, for the two output model at observation 36 are presented in tables 5.17 and 5.18 below. Canadian deliveries increase, according to the methodology discussed above, for one hypothetical firm (and decreasing for the other) across the table. Foreign deliveries, not documented in tables 5.17 and 5.18 due to space limitations, increase for one hypothetical firm (and decrease for the other) down the tables.

Table 5.17 Subadditivity Test Results for the Two Output Model, Observation 36[1].

Cdn = 0%	10%	20%	30%	40%	50%	60%	70%	80%	90%
-1.036	-1.035	-1.035	-1.034	-1.034	-1.033	-1.033	-1.033	-1.033	-1.033
-1.028	-1.028	-1.027	-1.027	-1.027	-1.026	-1.026	-1.026	-1.026	-1.026
-1.024	-1.023	-1.023	-1.023	-1.022	-1.022	-1.022	-1.022	-1.022	-1.022
-1.021	-1.021	-1.020	-1.020	-1.020	-1.019	-1.019	-1.019	-1.020	-1.020
-1.019	-1.019	-1.019	-1.018	-1.018	-1.018	-1.018	-1.018	-1.018	-1.018
-1.019	-1.018	-1.018	-1.018	-1.018	-1.018	-1.018	-1.018	-1.018	-1.018
-1.019	-1.018	-1.018	-1.018	-1.018	-1.018	-1.018	-1.018	-1.019	-1.019
-1.020	-1.020	-1.020	-1.019	-1.019	-1.019	-1.020	-1.020	-1.020	-1.021
-1.022	-1.022	-1.022	-1.022	-1.022	-1.022	-1.022	-1.023	-1.023	-1.023
-1.026	-1.026	-1.026	-1.026	-1.026	-1.026	-1.027	-1.027	-1.027	-1.028

Table 5.18 T-Ratios with 93 DF for the Two Output Model Subadditivity Tests, Observation 36.

Cdn = 0%	10%	20%	30%	40%	50%	60%	70%	80%	90%
-51.42	-52.29	-53.05	-53.70	-54.24	-54.64	-54.92	-55.06	-55.05	-54.89
-56.58	-57.57	-58.42	-59.12	-59.66	-60.03	-60.22	-60.22	-60.04	-59.67
-59.79	-60.84	-61.72	-62.42	-62.93	-63.23	-63.33	-63.21	-62.88	-62.34
-61.72	-62.79	-63.67	-64.34	-64.80	-65.04	-65.05	-64.83	-64.39	-63.73
-62.82	-63.87	-64.73	-65.36	-65.77	-65.95	-65.89	-65.60	-65.07	-64.32
-63.34	-64.35	-65.16	-65.75	-66.11	-66.22	-66.11	-65.75	-65.16	-64.35
-63.36	-64.32	-65.07	-65.60	-65.89	-65.95	-65.77	-65.36	-64.73	-63.87
-62.85	-63.73	-64.39	-64.83	-65.05	-65.04	-64.80	-64.34	-63.67	-62.79
-61.59	-62.34	-62.88	-63.21	-63.33	-63.23	-62.93	-62.42	-61.72	-60.84
-59.11	-59.67	-60.04	-60.22	-60.22	-60.03	-59.66	-59.12	-58.42	-57.57

The subadditivity test results, with T-ratios, for the three output model at observation 35 are presented in tables 5.19 and 5.20 below. interruptible service (N) is allowed to vary across rows and temporary winter service (not documented in tables 5.19 or 5.20 due to space limitations) is allowed to vary down the columns. The distribution of firm service is held

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1 Note that all tests which appear within the drawn box are duplicates of tests which appear outside of the box. This is expected and is evidence that the subadditivity test was preformed properly. Also note that this symmetry is present in the three output model subadditivity test results, but is much more difficult to observe given the three dimensional nature of the test matrix.

fixed between the two hypothetical firms at 0% and 100% in tables 5.19 and 5.20.

Table 5.19 Three Output Model Subadditivity Tests, Holding Firm Deliveries Constant, for Observation 35.

N = 0%	10%	20%	30%	40%	50%	60%	70%	80%	90%
-0.806	-0.881	-0.885	-0.887	-0.888	-0.889	-0.890	-0.891	-0.891	-0.891
-0.918	-0.960	-0.962	-0.963	-0.964	-0.964	-0.964	-0.965	-0.965	-0.964
-0.935	-0.972	-0.973	-0.974	-0.974	-0.975	-0.975	-0.975	-0.975	-0.974
-0.945	-0.978	-0.979	-0.980	-0.980	-0.980	-0.981	-0.981	-0.980	-0.980
-0.952	-0.983	-0.983	-0.984	-0.984	-0.984	-0.984	-0.984	-0.984	-0.983
-0.957	-0.986	-0.986	-0.987	-0.987	-0.987	-0.987	-0.987	-0.987	-0.986
-0.961	-0.988	-0.989	-0.989	-0.989	-0.989	-0.989	-0.989	-0.988	-0.988
-0.964	-0.990	-0.990	-0.991	-0.991	-0.991	-0.990	-0.990	-0.990	-0.989
-0.966	-0.991	-0.991	-0.991	-0.991	-0.991	-0.991	-0.991	-0.990	-0.989
-0.967	-0.990	-0.991	-0.991	-0.990	-0.990	-0.990	-0.989	-0.988	-0.987

Table 5.20 T-Statistics with 86 DF for the Three Output Cost Model Subadditivity Tests, Holding Firm Deliveries Constant, Observation 35.

N = 0%	10%	20%	30%	40%	50%	60%	70%	80%	90%
-8.1	-25.6	-27.8	-29.1	-29.9	-30.5	-30.9	-31.3	-31.5	-31.7
-27.4	-109.3	-117.6	-120.7	-121.8	-121.9	-121.4	-120.5	-119.2	-117.1
-39.2	-158.3	-166.9	-169.1	-169.1	-168.1	-166.8	-165.1	-163.1	-159.6
-49.5	-194.2	-201.1	-202.2	-201.6	-200.5	-199.2	-197.7	-195.9	-192.5
-58.3	-213.1	-217.9	-218.5	-218.1	-217.5	-216.8	-216.1	-215.1	-212.1
-64.6	-213.8	-217.3	-217.9	-217.9	-217.8	-217.7	-217.4	-216.4	-212.5
-68.2	-200.2	-202.7	-203.3	-203.5	-203.4	-203.1	-202.3	-200.2	-193.8
-69.1	-177.2	-178.8	-179.1	-178.9	-178.3	-177.2	-175.3	-171.5	-162.8
-67.6	-147.9	-148.5	-148.2	-147.4	-146.1	-144.2	-141.2	-136.3	-126.6
-63.5	-111.4	-111.1	-110.1	-108.8	-107.1	-104.7	-101.3	-96.4	-87.7

To summarize the results of all the subadditivity tests preformed, we need but note that all the predictions obtained were negative and highly significant. For the two output model, 360 unique subadditivity tests were preformed (for observations 30 to 36 inclusive) while in the three output model 2,190 unique tests were preformed (for observations 30 to 35 inclusive). All the results of the subadditivity tests confirm the natural monopoly hypothesis with a high degree of significance. We now turn our attention to interpreting the natural monopoly test results presented in this section.

5.5 Interpretation of Natural Monopoly test results

The results of the natural monopoly tests present a consistent view of TCPL. Namely, that TCPL is a natural monopoly, and as such should continue to operate exclusively in its markets. Results of these tests also provide an important insight into TCPL's costs as well. This will be discussed below, but first a summary of the natural monopoly test results is in order.

Panzar's (1989) tests of the necessary and sufficient conditions for natural monopoly provide evidence that TCPL is a natural monopoly. Recall the following three sets of conditions for a natural monopoly discussed in this thesis. Recall that economies of scale and scope form a necessary but insufficient condition for natural monopoly. Also recall that transray convexity combined with economies of scale forms a necessary and sufficient condition for natural monopoly. Finally, recall that cost complementarities is by itself a sufficient condition for natural monopoly. The econometric analysis of the TCPL data has provided us with estimates of scale economies which show TCPL to be experiencing increasing returns to scale. Though we have failed to show that TCPL experiences transray convexity in its cost structure, we have shown that TCPL experiences cost complementarities, and hence economies of scope. Economies of scope provide necessary evidence for natural monopoly while cost complementarities provides sufficient evidence for natural monopoly. Hence, we have shown both necessary and sufficient evidence to conclude that TCPL is a natural monopoly using Panzar's (1989) tests.

In addition to this, other test results support the conclusion that TCPL is a natural monopoly. Indeed, perhaps the most convincing evidences that TCPL is a natural monopoly are the results from the economies of scale test (in the single product setting) and the results of the subadditivity tests. Recall that in the single product setting economies of scale is a sufficient condition for a natural monopoly to exist. As we have found economies of scale in a single output cost function, we can conclude (from this fact alone) that TCPL is a natural monopoly. In addition to this result are the subadditivity test results. The Evans and Heckman (1984) test for subadditivity provides evidence that TCPL is a natural monopoly. The results of this test imply that if TCPL's output were split up between two smaller firms, industry costs would be significantly higher at all tested levels of total output. The natural monopoly status of TCPL is authenticated by the presence of subadditivity, economies of scale (in single, double, and triple output models), economies of scope and cost complementarities[1].

Knowing that TCPL is a natural monopoly, it is interesting to discuss why this is the case. Analyzing the results of Panzar's tests of the necessary and sufficient conditions for subadditivity allows us to discover this. Let us

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1 Which exists in this case, presumably as Sharkey (1982, p. 70) suggests, due to indivisibilities in inputs. That is, because inputs in the production process of a multiple output firm are not easily attributed to the production of any particular output.

begin the investigation by taking a closer look at the two output cost model.

In the two output case we have a monopolist, delivering natural gas to Canadian and foreign delivery points, which experiences economies of scale and scope. Now it is important to note here the physical composition of the pipeline network which accomplishes these deliveries. In particular we note that a single line carries gas from the Empress site in southern Alberta to several delivery points across Canada. Note that the pipelines which carry gas into the United states are linked to (branch off from) this main line, and do not originate from the Empress site directly. With this being the case, it may be said that economies of scope conveys the idea that it is cheaper to use this network type (a branching network) than to build separate pipelines for deliveries into the US which originate at the Empress site. This arises in the current application due to the presence of cost complementarities (brought about by the sharing of compressors and pipe[1] up to the point where branching into the US occurs). The presence of economies of scale, scope, and cost complementarities guarantees that the cheapest transportation of Canadian and foreign deliveries is accomplished by a single company employing a branching network technology. We now turn our attention to the three output model.

In the three output model, the outputs measured are: firm service, interruptible service and temporary winter service. Economies of scale, observed in this case, implies that the cheapest production of these services

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1 Recall that indivisibility in inputs (sharing of pipe and compressors) can yield cost complementarities.

is accomplished when they are produced jointly, with a single pipeline network. Varian explains this result,

> ... it is clear that if we double all inputs to the production process, the output may more than double since increasing the surface area of a pipe by 2 will increase the volume by a factor of 4 (1992 , p. 15).

Economies of scale tells us that it is better to build a single large pipe rather than several smaller pipes to carry the same volume of gas. Hence the delivery of all three types of service is accomplished most cheaply when done through a single large pipe (assuming that volumes increase when firm, interruptible and temporary winter services are provided jointly). Note that this implies economies of scope (Mansell and Church 1995, p.15). Further note that this also implies the sharing of common machinery (pipes and compressors) to produce multiple outputs, which implies cost complementarities as long as capacity constraints on individual machines are not binding (Sharkey, 1982, p.70). When we combine economies of scale, scope and cost complementarities we have necessary and sufficient conditions for TCPL to be a natural monopoly.

The presence of economies of scale, scope, and cost complementarities provide insightful information as to why we have found TCPL to be a natural monopoly.

An interesting anecdote which has come to light along this line of investigation is the unusual (and legitimate) finding of negative marginal costs in TCPL's smaller markets. This hints that TCPL may not be producing the lowest cost transportation that is possible given current technology. This result does not imply that TCPL is not cost minimizing, but does suggest that TCPL may lower its costs of transportation by expanding its markets in the areas of interruptible service, temporary winter service and in foreign deliveries.

This result allows the following conclusion to this thesis. The cost of transporting natural gas in Canada is lowest when it is preformed by a single company, namely TCPL, when compared to a hypothetical industry structure of two firms. However, this does not necessarily imply that TCPL is currently incurring the lowest possible costs for its transportation services. Indeed, both the two output and three output models in this thesis suggest that the total costs of transporting natural gas in Canada could decrease if TCPL expanded its smaller markets.

5.6 Summary of Conclusions & Prescriptions for Further Research

We have found that it is not a condition of a legitimate cost function that marginal costs be positive. Further, we may expect negative marginal costs to be observed if free disposal is not an option for the firm.

We have applied natural monopoly tests to TCPL and found that TCPL is a natural monopoly. However, we have also found that TCPL, though cost minimizing, may not be producing the lowest cost transportation in Canada.

We found that if TCPL expanded its' smaller markets (foreign, temporary winter service, and interruptible service) that TCPL's costs would decline.

Prescriptions for further research in this field include the following. Given that the absence of free disposal generates negative marginal costs, an attempt should be made to model disposal costs in the firms' cost function. Further, an attempt could be made to estimate TCPL's cost function using a more general functional form, for example the Box-Cox transformation of the Trans-log form. Such research could either confirm the results of this thesis or provide evidence that the results of this thesis are functional form specific. Finally, an attempt could be made at confirming the results of this thesis if, and when, a better and more complete data set comes available.

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Appendix 1

TCPL Ownership Information.

Table 6.1 Ownership holdings of TransCanada Pipelines Limited as of December 31, 1993.

Company Name	Type and % of Ownership	
392592 Alberta Ltd.	Subsidiary	100%
530230 Alberta Limited	Subsidiary	100%
879213 Ontario Limited	Subsidiary	100%
Alberta Natural Gas Company Ltd.	Investment	49.9%
Cancarb Gas Services Limited	Subsidiary	100%
Cancarb Limited	Subsidiary	100%
Foothills Pipe Lines (Sask.) Ltd.	Investment	44%
Great Lakes Gas Transmission System	Investment	50%
Iroquois Gas Transmission System	Investment	29%
Iroquois Pipeline Operating Company	Subsidiary	100%
Northern Border Pipeline Company	Investment	30%
Ocean State Power	Investment	40%
Polar Delta Project Ltd.	Investment	50%
Polar Gas Limited	Subsidiary	100%
Sable Gas Systems Limited	Investment	50%
Sunshine Interstate Pipeline Partners	Investment	30%
Sunshine Pipeline Partners	Investment	30%
Sunshine Pipelines, Inc.	Investment	30%
TCPL Cogeneration Ltd.	Subsidiary	100%
TCPL Hermiston Ltd.	Partnership	100%
TCPL Insurance Services Ltd.	Subsidiary	100%
TCPL Investments Ltd.	Subsidiary	100%
TCPL Ireland Financial Services	Subsidiary	100%

TCPL Mayflower Inc.	Subsidiary	100%
TCPL Mining Ltd.	Subsidiary	100%
TCPL Power Ltd.	Subsidiary	100%
TCPL Project Engineering Ltd.	Subsidiary	100%
TCPL Storage Ltd.	Subsidiary	100%
TCPL SunShine Inc.	Subsidiary	100%
TCPL SunShine Interstate Inc.	Subsidiary	100%
TCPL Tuscarora Ltd.	Subsidiary	100%
TCPL Ventures Ltd.	Subsidiary	100%
TQM Pipeline Partnership	Investment	50%
Trans Quebec & Maritimes Pipeline Inc.	Investment	50%
TransCan Finance Alberta Ltd.	Subsidiary	100%
TransCan Holdings (1991) Ltd.	Subsidiary	100%
TransCan Northern Ltd.	Subsidiary	100%
TransCanada Border PipelLine Ltd.	Subsidiary	100%
TransCanada GL, Inc.	Subsidiary	100%
TransCanada Iroquois Ltd.	Subsidiary	100%
TransCanada PipeLine Division Limited	Subsidiary	100%
TransCanada PipeLine USA Ltd.	Subsidiary	100%
TransCanada PipeLines Argentina Limited	Subsidiary	100%
TransCanada PipeLines Finance USA Ltd.	Subsidiary	100%
TransCanada PipeLines Investments (Quebec) Inc.	Subsidiary	100%
Western Gas Marketing Inc.	Subsidiary	100%
Western Gas Marketing Limited	Subsidiary	100%
Western Gas Services Limited	Subsidiary	100%

Appendix 2.

Proof of concavity following from cost minimization.

The firms' cost function is given by:

$$C(y,w)$$

Concavity of this function is given by:

$$C(y,w) \geq tC(y,w^{\circ}) + (1-t)C(y,w^{1})$$

where w° and w^{1} are a linear combination of w such that $tw^{\circ} + (1-t)w^{1} = w$, with $0 < t < 1$.

Now suppose that associated with w there exists an optimal bundle of productive inputs, x. Then the firms' costs can be described as:

$$C(y,w) = \Sigma wx$$

Expanding this along a linear combination of input prices yields:

$$C(y,w) = \Sigma wx = t\Sigma w^{\circ}x + (1-t)\Sigma w^{1}x$$

such that $tw^{\circ} + (1-t)w^{1} = w$.

Now consider:

$$C(y,w^{\circ}) = \Sigma w^{\circ}x^{\circ}$$

where x° is the cost minimizing input bundle associated with input prices w°. We know that due to this being the cost minimizing bundle that:

$$C(y, w^{o}) = \Sigma w^{o}x^{o} \leq \Sigma w^{o}x \qquad 6.1$$

and, by analogy that:

$$C(y, w^{1}) = \Sigma w^{1}x^{1} \leq w^{1}x \qquad 6.2$$

Multiplying equation 6.1 by t and equation 6.2 by (1-t), and summing the two resulting equations yields:

$$t\ \Sigma w^o x^o + (1-t)\ \Sigma w^1 x^1 \leq t\ \Sigma w^o x + (1-t)\ \Sigma w^1 x$$

This is, by definition,

$$\boldsymbol{C}(y, w) \geq t\ \boldsymbol{C}(y, w^o) + (1-t)\ \boldsymbol{C}(y, w^1)$$

which is the definition of concavity as given above.

Appendix 3

The idea that marginal cost must be positive has its roots in microeconomic theory. From duality theory, expenditure functions must be increasing in utility (Gravelle and Rees, 1992, p 110). Since cost functions are the firms expenditure function, it follows that cost must be increasing in output, and hence that marginal cost must be positive (Gravelle and Rees 1992, p. 203). This analogy has been assumed by some to carry over to multiple-output production[1]. However, this analogy is flawed in the case of multiple-output production.

In the single output case, the firms cost minimization problem is given by:

(1) $$C(w,Y) = \min\ [xw + \lambda(f(x)-Y)]$$

Where: C is the cost function
w is the vector of input prices
x is the vector of input quantities
f is the production function
λ is the lagrange multiplier
Y is the SCALAR output measure

It follows from the Envelope theorem that:

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1 See for example Shin and Ying (1992), Roller (1992) and Ellig and Giberson (1993).

(2) $$\lambda = \frac{\partial C}{\partial Y} = MC$$

Further, since the firm's optimization problem is a concave programming problem[1], it follows that λ and marginal cost are both non-negative (Gravelle and Rees, 1992, p.45).

Now let us consider the multiple output case. Let $\phi(x,y)$ represent the production technology where y is the vector of outputs. The firm's cost minimization problem then is denoted:

$$C(w,y) = \min\ [xw + \lambda\phi(x,y)]$$

Differentiating with respect to y_i yields the marginal costs of production,

$$\frac{\partial C(w,y)}{\partial y_i} = \lambda\frac{\partial\phi(x,y)}{\partial y_i} \quad ,\forall i$$

Knowing that $\lambda \geq 0$ is insufficient information to sign $\partial C/\partial y_i$. Shephard (1970, p. 227) uses set notation and production correspondences to derive regularity conditions for a proper cost function under multiple output production. Only two regularity conditions for a cost function with respect to outputs are presented by Shephard. One of those is:

$\overline{Q.11}$ C(w,y) is convex in y ..., if the graph of P is convex (1970, p.227).

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1 This merely restricts the production function to be concave in x, inputs.

Shephard states:

> Convexity of the graph (of P) is unnecessarily restrictive, implying nonincreasing returns to scale for the related production function (1970, p.197).

Which only allows us to state that if returns to scale are nonincreasing (and if the graph of P is convex) that marginal cost is increasing. This allows us to sign $\partial C^2/\partial y_i^2$ in one special case, and does not allow us to sign $\partial C/\partial y_i$.

In addition, Shephard (1970) supports the idea that marginal cost need not be positive in the multiple output production case. He presents the following regulartiy condition:

$\overline{Q.8}$ a) For any $w \subseteq X$, $C(w, \theta y) \geq C(w,y)$ for $y \subseteq Y$ *and* $\theta \subseteq [1, +\infty)$

or/and

b) For any $w \subseteq X$, $C(w,y') \geq C(w,y)$ for $y' \geq y \subseteq U$

(1970, p.227)

Where: X and U are the sets of input prices and output quantities defined by efficient production,

y is the vector of outputs,

w is the vector of input prices,

Property b) can be interpreted as saying marginal cost is not negative (as equation (2) above states), which can BUT NEED NOT follow from property a).

Property a) can be interpreted as saying that cost should not decrease when the scale of production increases.

Shephard continues, "(this property) has two forms depending upon whether the (production) correspondence has weak or strong disposal of outputs (1970, p. 228)", "property (a) holds under weak disposal and property (b) holds under strong disposal (1970, p. 187)." Note that because property (a) may hold without property (b) holding, it follows that positive marginal cost is a sufficient but not a necessary regularity condition for a multiple output cost function. What is necessary is that cost should increase if the scale of production increases, that economies of scale should be strictly positive.

Panzar (1989, p.8) has suggested a test for economies of scale in a multiple output setting. This test is:

$$S(y,w) = -\frac{\left[\lambda \Sigma x_i^* \dfrac{\partial \phi(x,y)}{\partial x^*}\right]}{\left[\lambda \Sigma y_j \dfrac{\partial \phi(x,y)}{\partial y_j}\right]} = \frac{C(y,w)}{\Sigma y_j C_j(y,w)}$$

We can interpret S(y,w) as saying, if scale economies are present, and we look along a ray from the origin, average costs along that ray are falling. Hence output-weighted marginal costs are below total cost so that S > 1. Conversely, if diseconomies of scale are present S < 1, and if there are constant returns to scale, S = 1.

Shephard's condition in a multiple output setting informs us that S ≥ 0 is a necessary regularity condition for a legitimate cost function in a multiple output setting. Further notice that, according to Panzar's test of economies of scale, strictly positive marginal cost gurantees this, but is not necessary for this to occur.