ECONOMIES OF SCALE AND SCOPE IN MULTIPRODUCT INDUSTRIES: A CASE STUDY OF THE REGULATED U.S. TRUCKING INDUSTRY

by

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ABSTRACT

For multiproduct industries such as the U.S. trucking industry, economies in production could exist due to output quantity (economies of scale) as well as joint production of outputs (economies of scope). Conventional studies of trucking technology treat trucking as a single-output production and ignore the quality differentials in output. This has led to biased and unsatisfactory empirical results. This study is the first to explicitly consider trucking output as a vector of different products in the cost function specification, and to attempt to directly measure the impacts of network structure and network operations upon carriers' costs. A multiproduct joint cost function has been proposed and estimated from a cross section of general-freight common carriers. The empirical results show that the use of network variables and output disaggregation substantially improves the empirical analysis.

Previous studies of trucking costs have suggested that interregional general-freight carriers face slightly increasing returns to scale. This study indicates that there is no empirical evidence of economies of scale in the U.S. trucking industry, but that there is evidence of economies of scope. These economies of scope arise from economies of network configuration (extensiveness) and economies of network operation (intensiveness or density), as well as from shared inputs. The empirical evidence of this study suggests that 1) there are cost advantages associated with a high degree of network connectivity, which brings about efficiencies through direct-routing strategies; and these cost advantages increase with firm size since larger firms are better able to provide direct service; and 2) cost advantages result also from better routing and terminal consolidation practices; in other words, there are returns to traffic density. Both economies of network configuration and economies of network operation explain the recent merger and acquisition activity from a cost perspective. This study concludes also that general-freight carriers have no perceptible tendency to behave as natural monopolists in a deregulated environment.

It should be stressed that the methodology and procedures developed in this study can be applied to other sectors of the transportation industry, as well as to other multiproduct industries.

Thesis Supervisor: Ann F. Friedlaender
Professor of Economics and Civil Engineering

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Finally, I would like to take this opportunity to show my love to my husband Yu-Sheng and my two children Jimmy and Tony for all the days they tolerated my neglecting them during very important parts of their lives. Without Yu-Sheng's continuous encouragement to try to find out the world of myself and to develop my potential, I could still be a housewife. Jimmy's and Tony's excellent performance at school have also given me much comfort to continue to concentrate on my work in these days. I should love them even more!

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CHAPTER ONE

INTRODUCTION

The passage of the trucking regulatory reform bill in the summer of 1980 has focused attention on the competitive behavior of the regulated trucking industry. The extent to which regulation encourages or discourages competitive behavior on the part of common carriers of general commodities is a question that has aroused considerable controversy. Economists generally believe that the fixed costs of these carriers are not particularly high and that their capacity can be easily adjusted and readily transferred from one market to another. Thus there is no reason to believe that these carriers should be characterized by increasing returns to scale. Therefore, in the absence of regulation, there is a wide sentiment among economists that the general commodity carriers would be competitively organized, with a large number of relatively small carriers serving any given market.

However, opponents of deregulation argue that there are not only economies of scale but also economies of network density in the regulated commo carriers of general commodities. Since less-than-truckload (LTL) trucking operations require extensive terminal consolidation through vast networks, the investment needed for these firms is substantial. Consequently, significant cost advantages exist for firms with large outputs and dense traffic networks. Thus this view holds that in the absence of regulation, the industry would be concentrated in the hands of a few carriers and that prices would be too high and quantity of output too low relative to the competitive norm, especially in low-traffic, low-density areas.[1]

In analyzing the existence of scale economies empirically, it is useful to examine the cost structure of the given industry. Although there have been many econometric studies of the cost functions of the common carriers of general commodities and their implied scale economies, the empirical findings have not been conclusive. Recent studies tend to indicate that the small, regional carriers of general commodities are likely to exhibit slightly decreasing returns to scale, while the large, interregional carriers seem to face weak and statistically insignificant increasing returns to scale.[2]

In fact, however, a substantial number of interregional and transcontinental carriers are quite large, with outputs well in excess of 500 million ton-miles. Moreover, over the past 10 or 15 years, these large carriers have tended to grow substantially relative to their smaller competitors, both through mergers and acquisition as well as internal growth. The corridor concentration ratios that were recently released by the Senate Judiciary Committee (1980) indicate that the general-freight trucking industry is highly concentrated and differs substantially from the competitive str ture predicted by economists. As shown in Figure 1.1, in terms of aggregate annual revenues, the four largest general-freight carriers — which repre-

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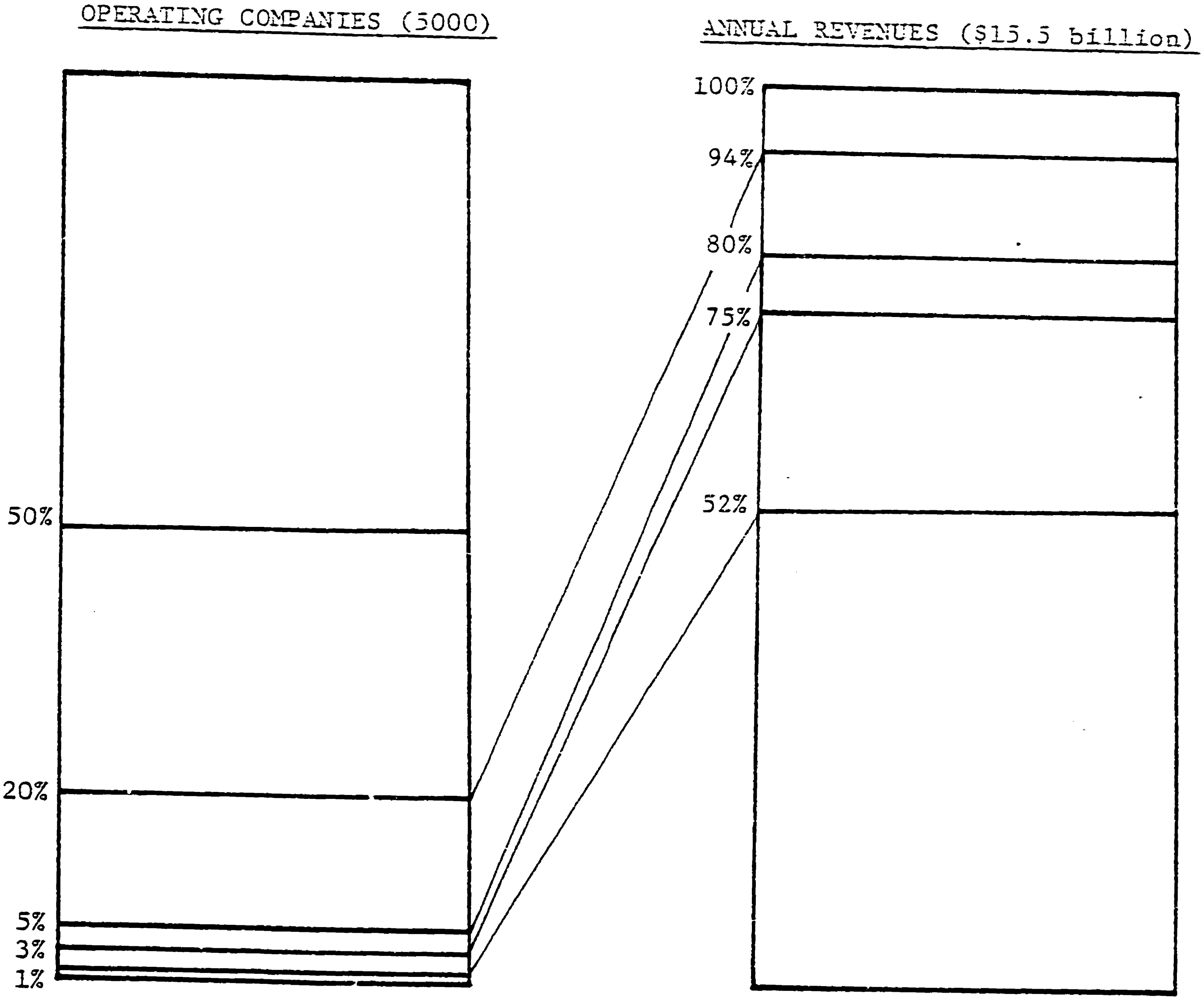
[1] For a good survey of the various pros and cons of regulation see National Research Council (1978) and Senate Judiciary Committee (1980).

[2] See Spady and Friedlaender (1978), Wang Chiang (1979), and Friedlaender, Spady and Wang Chiang (1981). In addition, see Chow (1978). These studies are reviewed in Chapter Three.



Less than 1% of the carriers earn more than half of the industry's revenues

80 percent of the firms earn only 6% of the industry's total revenues

Figure 1.1. Concentration among Common Carriers of General Freight

Source: Committee on the Judiciary, "Federal Restraints on Competition in the Trucking Industry: Antitrust Immunity and Economic Regulation," 1980, p. 101.

sent 0.08 percent of all such carriers — accounted for more than 15 percent of total revenues during 1976—1977. The eight largest firms accounted for nearly 23 percent. And, less than 1 percent (i.e., 45) of the general-freight carriers earned more than half the revenues of that industry segment. In addition, the 4-firm concentration ratios on most corridors were well above 50 percent, indicating that the four largest carriers in any corridor tended to dominate its traffic.

In spite of this evidence of economic power and concentration, it would be a mistake to conclude that the interregional common carriers exhibit scale economies and thus should be regulated to avoid monopoly power and poor service in low-density rural communities. Apparently, the per-unit cost advantages of large firms in carrying LTL traffic come from large loads and long lengths of haul. Large firms are better able to schedule their traffic and utilize their fleets to obtain higher loads and longer hauls because they have more operating rights. Since regulation prescribes the corridors over which these regular-route carriers can travel, regulatory restrictions on operating rights may encourage excessive concentration within any given corridor. Thus the observed levels of concentration among the interregional common carriers of general commodities may be primiarly due to regulatory restrictions on operating rights instead of basic technological conditions.

The inability of empirical studies to provide conclusive econometric evidence on the existence of economies of scale arises mainly from the heterogeneity of trucking output. The output of a trucking firm is multidimensional by its very nature. Trucking is not a physical, final good. Rather, it is a service performed through a network and is highly characterized by its quality differentials. This suggests that trucking technology can be better understood if it is modeled as a multiple output production process and the implications of network operations on trucking costs are explicitly considered. However, conventional studies have treated trucking output as being homogeneous and generally ignored the quality dimensions. The effects of network operations upon trucking costs have also been neglected. Thus existing empirical work on the trucking industry does not provide a sufficiently rich framework to analyze fully the economies associated with large firm size and network.

The most satisfactory existing approach to modeling trucking costs uses general flexible-form cost functions, which introduce a number of aggregate vari bles to measure the quality dimension of trucking operations.[3] Instead of treating heterogeneous trucking outputs as multiple outputs directly, recent studies attempt to model the output vector as an aggregate output with a vector of hedonic variables to describe the output mixture. This approach has been successful in avoiding many a priori restrictions on the specification of the cost function and in providing evidence on the effects upon costs of operating characteristics such as average length of haul, average load per vehicle, LTL percentage, etc. However, it has been less successful in providing a full understanding of product mix and network effects upon costs. Unfortunately, it is these two pieces of information that are crucial to understanding the technology and economies of scale of trucking firms, especially the large interregional and transcontinental carriers.

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[3] Examples can be found in Chapter Three, Section II, below. See also Friedlaender, Spady (1981), and Friedlaender, Spady and Wang Chiang (1981).

This study presents the results of current research on the structure of costs and technology of the regulated interregional/transcontinental carriers of general commodities. The study considers explicitly, for the first time, trucking output as a vector of different products, ecah with its own quality attribute, and also tries to measure directly for the first time the impacts of network structure and network operations upon these carriers' costs. A multiple-output cost function has been estimated from a cross section of these general-freight carriers in 1976. The purpose of this study is to provide new insight into the technology of these carriers which is not only useful in explaining the nature of economies of large size and thus of tendencies toward concentration in this industry, but also is useful in inferring the possible industry structure that would occur in a deregulated environment. The specific policy issues to be answered include the following:

- Is the high concentration ratio among general-freight carriers caused by inherent economies associated with the technology, or by regulatory constraints on entry? Would the degree of concentration continue to increase or would it decline in the absence of regulation?
- Do large carriers enjoy per-unit cost advantages over smaller carriers, particularly in long-haul markets? If so, where do these cost advantages come from?
- Are there cost complementarities among various types of general-freight trucking service — long-haul service, short-haul service, truckload service, and LTL service?
- Has the general-freight trucking industry a tendency toward natural monopoly?

The answers to these questions require both a conceptual discussion of the nature of size-related economies in the trucking inudstry and a careful empirical analysis of costs that captures the effects of network structure and heterogeneous output. Thus considerable groundwork must be laid before the policy implications of the analysis can be discussed.

This thesis takes the following structure. Chapter Two provides a brief institutional background and discusses the structure of the trucking industry and the role that regulated carriers of general commodities play in it. Chapter Three presents a review of the existing literature concerning trucking costs and summarizes the empirical evidence with respect to scale economies and the structure of trucking costs. Chapter Four then discusses how the concept of scale economies must be modified in the context of a multiple-output firm and provides a theoretical framework for the subsequent empirical and policy analysis. Chapter Five discusses the specification of the multiproduct cost function for the trucking industry and the nature of the variables that enter as its arguments, while Chapter Six discusses the preparation of a data base and the empirical results and their implications for the structure of trucking technology. Chapter Seven then discusses the policy implications of the analysis and presents a brief summary and conclusion.

CHAPTER TWO

STRUCTURE OF THE U.S. TRUCKING INDUSTRY AND SIZE-RELATED ECONOMIES

I. Structure of the Industry

The trucking industry in the United States is not a homogeneous, collective entity, but is characterized by a wide diversity of functions, organizational structures, and regulatory arrangements. Thus the existing U.S. trucking industry can be classified into seven major sectors, each distinguished by its operating authorities and characteristics. These sectors are:

- Common carriers of general commodities (ICC-regulated)
- Common carriers of special commodities (ICC-regulated)
- Contract carriers (ICC-regulated)
- Intrastate and local carriers (state or local regulated)
- Private carriers (unregulated)
- Exempt agricultural haulers (unregulated)
- Owner-Operators (unregulated)

Owner-operators, the last category, are independent carriers and can operate in one or more of the other categories listed above. However, they typically work as exempt agricultural haulers and frequently lease themselves and their vehicles to irregular-route, special-commodity carriers or contract carriers. Under the Interstate Commerce Commission (ICC) Act, common carriers of general commodities, common carriers of special commodities, and contract carriers are regulated by the ICC. These ICC-regulated carriers are estimated to carry about 40 percent of total intercity trucking ton-miles. For-hire carriers which are exempted from the ICC regulation include agricultural haulers which can carry only limited agricultural goods, state or local carriers which can operate only within states or defined areas, as well as owner-operators. The structures of these trucking segments and their market shares are shown in Figure 2.1.[1/]

Each trucking segment is characterized not only by its distinct mode of operation and underlying technology, but also by its operating authority. The major operating characteristics and a typical map of the operating authority of each segment are summarized and illustrated in Figure 2.2. The operating characteristics of general-commodity and special-commodity carriers are significantly different from each other. Common carriers of general freight serve points through a fixed route network, typically use union labor, and carry substantial amounts of less-than-truckload (LTL) traffic. They need labor-intensive consolidation operations in local terminals. In contrast, carriers of specialized commodities deal almost exclusively in full-truckload (TL) traffic. Without the need for specialized labor at distribution terminals or scheduled service on fixed point routes, they rely more on non-union labor and particularly on rented owner-operators. Common carriers of special commodities are further classified into groups according to the types of commodities being carried. These carriers are usually characterized by their specialized operations and/or equipment. Compared to these special-commodity carriers, general-commodity carriers are far more homogeneous. However, the within-group heterogeneity in common carriers of

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[1/] More detailed description of the structure of the trucking industry can be found in Wyckoff and Maister (1975), Wyckoff (1979), Chow (1978), Roberts (1977), and LaMond (1980).

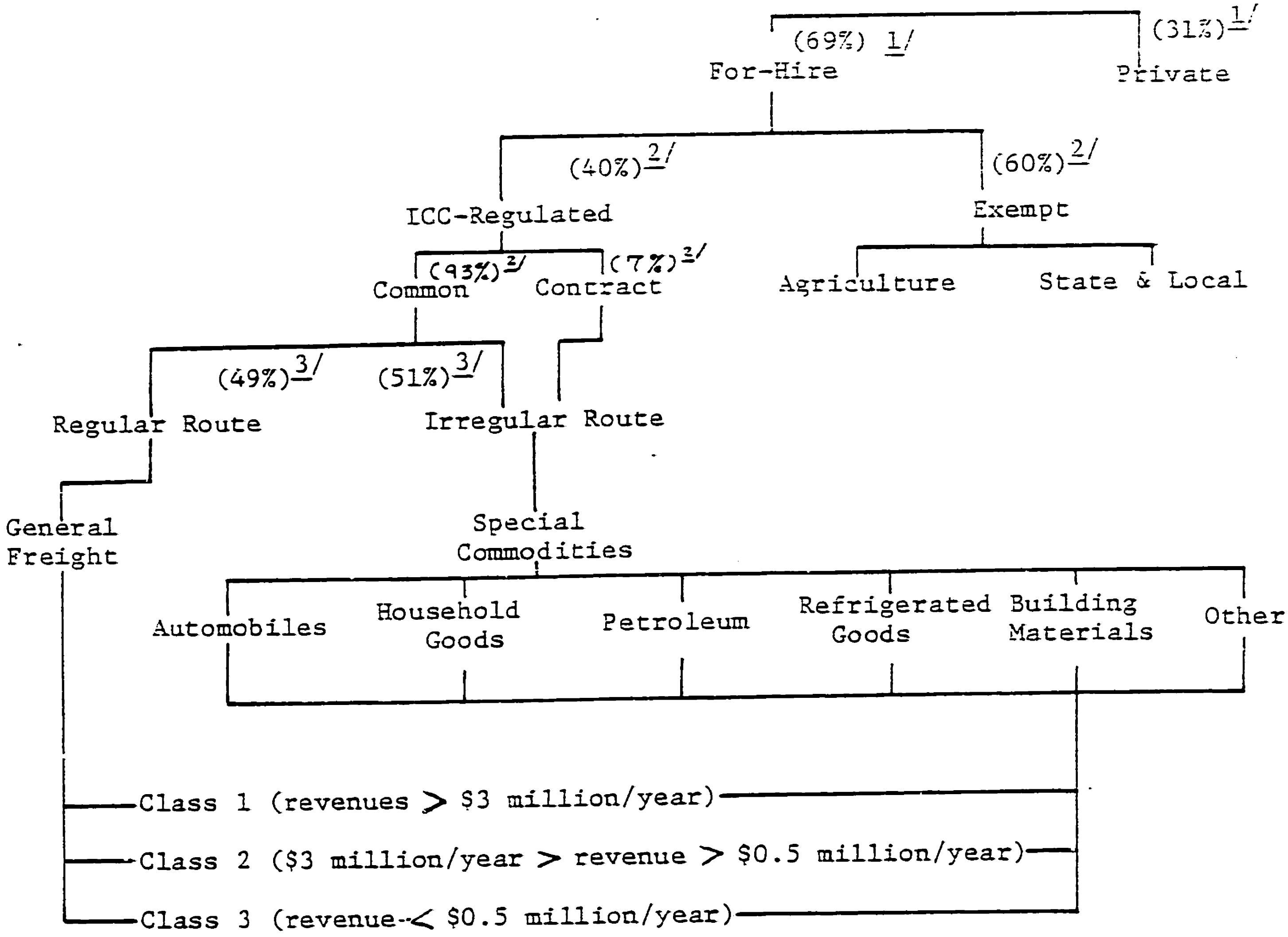


Figure 2.1 The Structure of the Interstate Motor Carrier Industry

Source: Wyckoff and Maister, The Owner-Operator: Independent Trucker, 1975, p.

Percentages are added from various sources as indicated:

1. P. Roberts, "Some Aspects of Regulatory Reform of the U.S. Trucking Industr 1977, p. 6; percent of total ton-miles.
2. A. LaMond, Competition in the General-Freight Motor-Carrier Industry, 1980, pp. 10-12; percent of intercity ton-miles.
3. Trinc's Blue Book of the Trucking Industry (1967-77), Washington, D.C.

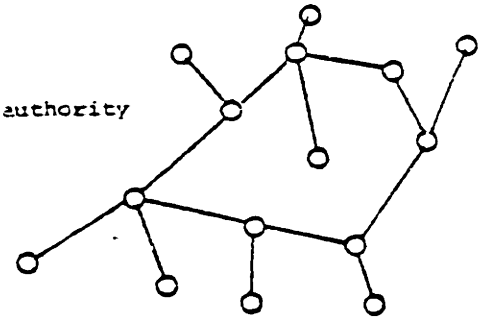
gure 2.2 CHARACTERISTICS OF THE INDIVIDUAL SEGMENTS MAKING UP THE U.S. TRUCKING INDUSTRY

CHARACTERISTICS

TYPICAL MAP OF OPERATING AUTHORITY

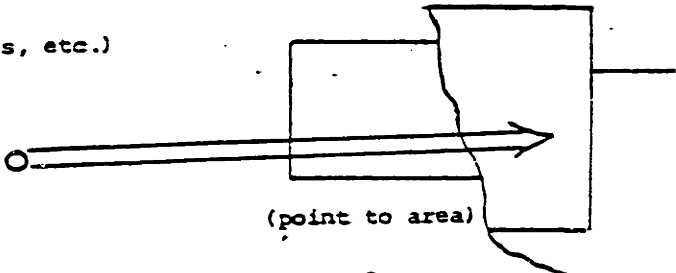
Regular Route Common Carriers of General Freight

General Commodities
Points served and routes travelled specified in detailed map of authority
Regular Service an obligation
Consolidation terminals and pickup and delivery fleets typical
Heavily unionized in both drivers and dock workers
Typically a party to the teamster Master Freight Agreement
Large Portion of revenue from LTL shipments
Not much use of owner operators



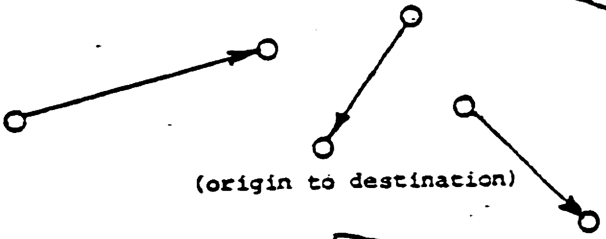
Irregular Route Special Commodity Carriers

Special Commodities (petroleum autos, household goods, etc.)
Point to area definition of authority
Irregular service on demand
No consolidation terminals
Full truckload operations
Non-unionized work force
Heavy use of owner operators



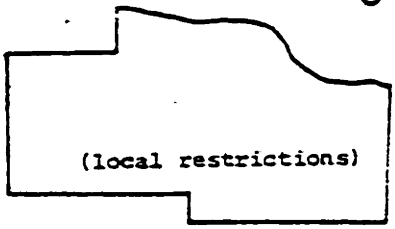
Contract Carriers

Specialized service
Limit on number contracts (8-12)
Dedicated equipment
Long-term of commitment
Some use of owner operators



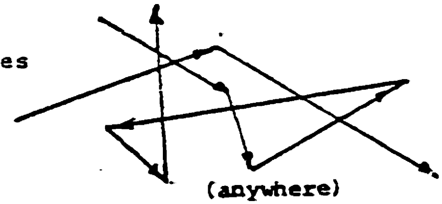
Intrastate and Local Carriers

Regulated by state or local P.U.C.
Limited area of service
Local cartage operations typical
Highly diverse operations
Frequently specialized (sand and gravel, concrete, etc.)



Exempt Agricultural Haulers

Limited to special products
Agricultural cooperatives can haul some regulated commodities
Anyone can provide service
Anywhere in U.S.
Typically full truckload
Owner operators typical



Owner Operators

(none)

Own their own vehicle (or lease it)
Can always work as agricultural exempt hauler
Frequently lease themselves and vehicle to Irregular Route Carrier or Contract Carrier
Illegal to lease to private carrier
Independent entrepreneur, typically 75/25 percent revenue split
Typically high equipment utilization and low costs

Private Carriers

(own account)

Own or lease vehicles (Illegal to lease vehicles with drivers)
Can haul only products they own
Cannot haul for other corporate subsidiaries
Both union and non-union labor typical
Tremendous diversity in manner of operation
May lease equipment to regulated carriers

Source: Roberts (1977), p. 6.

general commodities is still very significant. They present substantial differences in firm size, network configuration, the nature of terminal operations, the level of service quality, and so forth. Empirical evidence shows that the extent of the heterogeneity in common carriers of general commodities has led the industry to exhibit substantially different technologies and operating costs.

The dimensions of ICC regulations upon general-freight carriers include entry, exit, mergers, acquisitions, routes, points served, commodities carried, rates, and a variety of other factors. The Motor Carrier Act of 1935 established the standards, requirements and procedures for these dimensions and introduced the federal regulation of interstate motor carriers. While these dimensions have been modified somewhat by subsequent legislation, the structure of motor carrier regulation has remained remarkably constant over the last 45 years. Under ICC regulation, an operating authority will be required in order to enter the industry, and the authority is granted through one of three ways: 1) under the "grandfather" provisions of the act; 2) by an approved merger or acquisition; or 3) by meeting the statutory standards for entry as interpreted by the ICC. Carriers already operating at the time the act became effective received "grandfather" operating authority by meeting certain criteria. A new carrier seeking to enter the regulated trucking industry as a common carrier, or to expand the scope of its operations, must meet two statutory tests. First, it must convince the ICC that it is "fit, willing, and able to provide the transportation to be authorized by the certificate." Second, it must show that the transportation to be provided under the certificate is or will be "required by the present or future public convenience and necessity." The first test is intended to protect the public from unscrupulous and unstable operators. The second test, on the other hand, is directed mainly toward protecting existing carriers from new and unwanted competition.[2/] However, the recent Motor Carrier Act of 1980 has made the second test less stringent in an effort to ease the restiictions on entry that have traditionally existed.

The "grandfather" operating authority, the statutory tests for entry and concern with the profitability of existing carriers, plus the ambiguity, uncertainty, and time consumed in the certification process have tended to make new entry into the regulated trucking industry extremely difficult. Thus entry into new markets has tended to take place through mergers and acquisitions. Consequently, regulation has tended to contribute to the increasing levels of concentration that have been observed in the industry. Although the Motor Carrier Act of 1980 should reduce the regulatory barriers to entry and thus make it more competitive, the effective impact of this new legislation has yet to be established.

General-commodity carriers predominately or exclusively haul "general freight" as defined by the ICC commodity classification shown in Figure 2.3. Special-commodity carriers exclusively haul one or several kinds of specialized freight for which they have been granted ICC authority. A special-commodity carrier cannot carry general freight. According to ICC classification, the type of service of a common carrier can be regular route or irregular route. General-freight carriers typically provide regular-route services

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[2/] Senate Judiciary Committee Report (1980), pp. 28-30.

Figure 2.3 Classification of Motor Carriers by Type of Commodity Transported

1. Carrier of general freight
2. Carrier of household goods
3. Carrier of heavy machinery
4. Carrier of liquid petroleum products
5. Carrier of refrigerated liquid products
6. Carrier of refrigerated solid products
7. Carrier engaged in dump trucking
8. Carrier of agricultural commodities
9. Carrier of motor vehicles
10. Carrier engaged in armored truck service
11. Carrier of building materials
12. Carrier of films and associated commodities
13. Carrier of forest products
14. Carrier of mine ore, not including coal
15. Carrier engaged in retail store delivery service
16. Carrier of explosives or dangerous articles
17. Carrier of specific commodities, not subgrouped

Source: ICC, Classification of Motor Carriers of Property, 1937.

while special-freight carriers typically provide irregular-route service. However, a general-commodity carrier may also possess authorities to transport one or more special commodities and/or to travel through irregular routes. In most cases, a general freight authority specifies points to be served and the particular routes which a carrier must follow between two points.

The ICC requires motor carrier rates to be "reasonable, compensatory and non-discriminatory." All regulated carriers have to file their tariffs with the ICC for any proposed rate change. The ICC is authorized to review these rates and to set, if desirable, the maximum, minimum or specific rates for the carriers. In most cases, proposals of rate change have been made through rate bureaus — trade associations of regulated motor carriers which collectively process rate proposals and publish joint tariffs charged by their member carriers.

Almost all general freight is handled through so-called class rates. Class rates are not commodity-specific but are set for broad categories of freight with similar transportation characteristics with respect to value of commodity and cost of shipping and handling. However, the relationship between rates and costs is often quite loose, and rates for LTL shipments do not, in general, reflect their costs. For example, LTL shipments with significantly different lengths of haul could well be charged, in many situations, with the same rate per hundred weight. Moreover, since considerable amounts of time are usually required to adjudicate a rate proposal,[3] carriers have not been able, in practice, to adjust their rates on a competitive, cost basis.[4] Thus rates on some shipments fail to cover their costs while rates on other shipments may be highly profitable. Although there is considerable controversy concerning the relationship of rates to costs, it is generally believed that long-haul, high-volume shipments are highly profitable, while rates on short-haul, small shipments are not.[5]

The operations of general-commodity carriers handling LTL traffic can be summarized as follows. The authority granted for a carrier specifies both the points of origin and destination of freight, and the particular routes between cities over which it may travel. Since the carrier handles mainly smaller, LTL shipments, it is economic to consolidate shipments into full truckloads to move over scheduled linehaul, intercity truck routes. The firm may choose to consolidate shipments via the line vehicles, or alternatively, at fixed terminal points, with the latter being generally used. For the carrier that serves multiple destinations from multiple origins, vehicles can be further reconsolidated en route at breakbulk terminals. The flow of shipments between origin points and destination points through pickup/delivery and linehaul vehicles over a network with consolidation and breakbulk terminals is illustrated in Figure 2.4. The pickup, delivery, and terminal operation activities are described in detail in Figure 2.5

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[3] Independent rate proposals may require 2 or more years to be resolved. Many bureau-set rates are protested and suspended as well. (Judiciary Committee Report, 1980, p. 96).

[4] See, for example, Boyer (1981).

[5] See, for example, LaMond (1980).

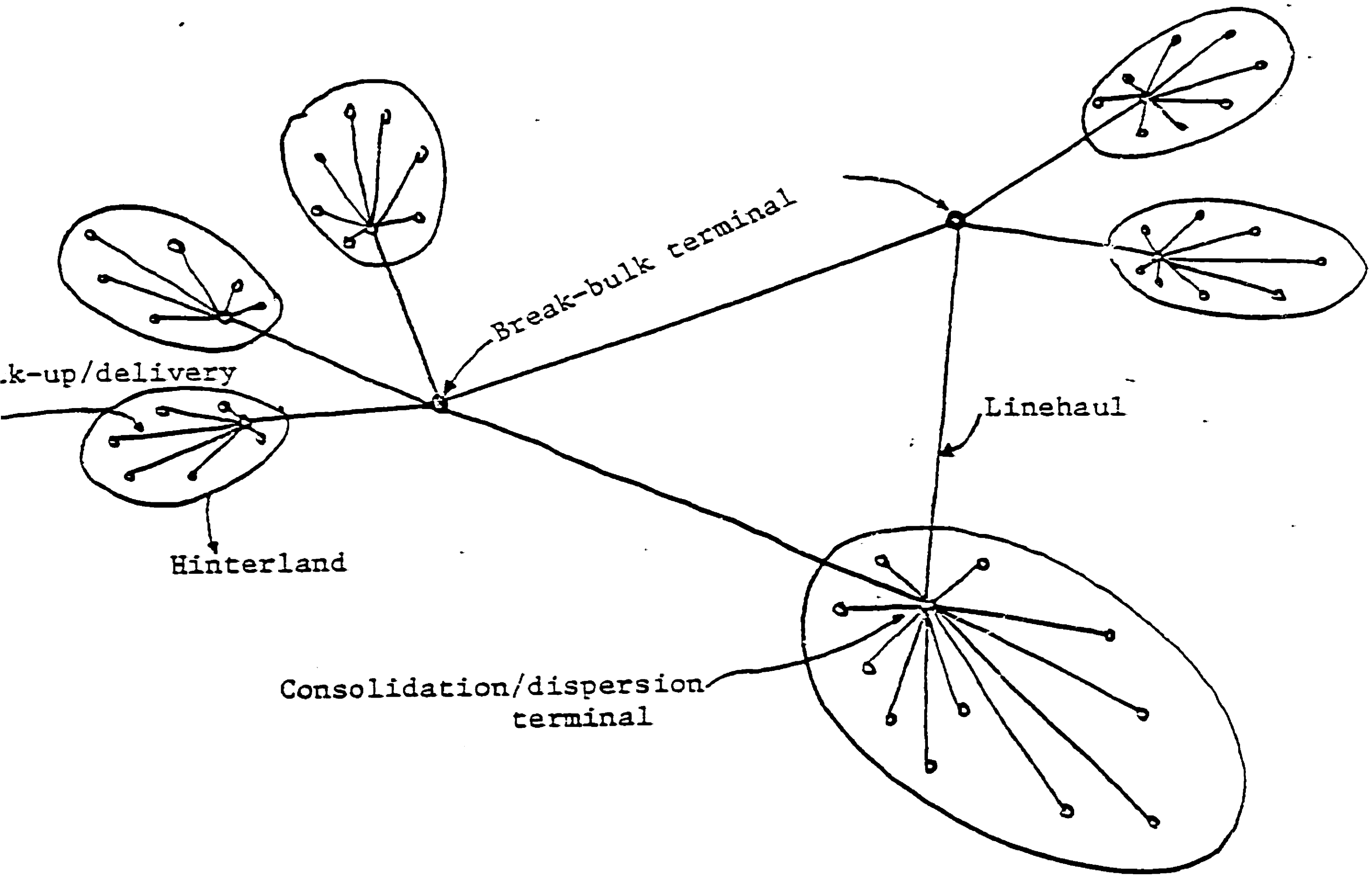
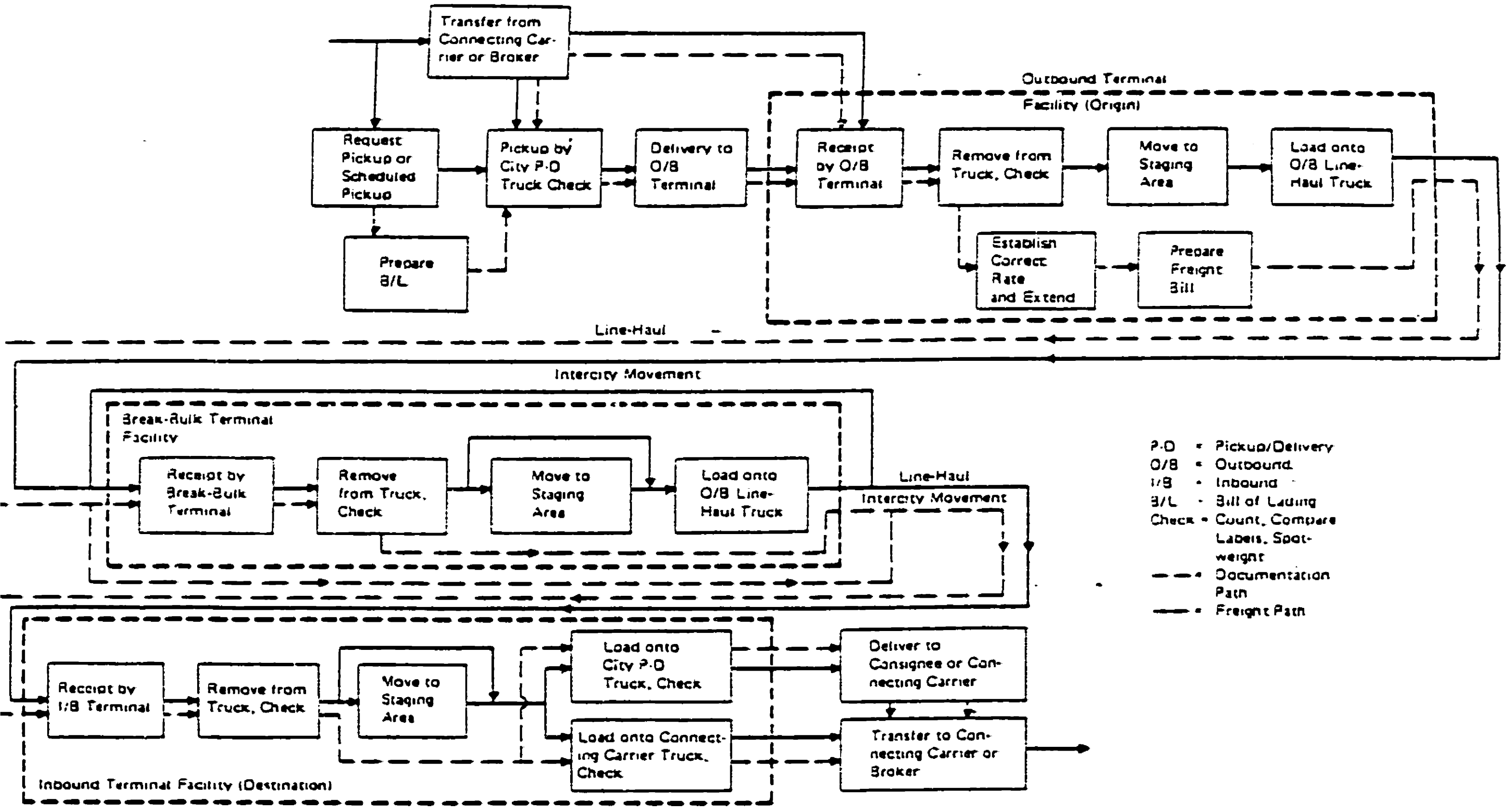


Figure 2.4 Network operations of a common carrier of general commodities



Schematic of Flow of Less-Than-Truckload Intercity Shipment Through a General Commodities Carrier Operation.

Figure 2.5

Source: D. Daryl Wyckoff, Organizational Formality and Performance in the Motor Carrier Industry, Lexington Books, 1974, p. 17.

II. Size-Related Economies in the Trucking Industry

Economies of scale traditionally refer to situations where long-run average cost decreases as output is increased.[6] Thus in the presence of significant economies of scale, a large carrier can produce with lower costs than smaller competing carriers and thus dominate the market. In the absence of regulation, the monopoly power of the dominant firm will cause the price to be too high and the quantity of output too low relative to their competitive levels.

There is significant controversy over whether economies of scale exist in the trucking industry. The bases for arguing for decreasing costs in the trucking industry have been the following:[7]

- Trucking firms operate integrated and often geographically vast networks. The movement of LTL shipments through such networks requires substantial investment in numerous terminals and intermediate point freight handling facilities.

- In the presence of fluctuating demand, the larger carrier may have advantages in traffic solicitation and greater control over equipment movements, leading to better equipment and manpower utilization. In addition, a larger carrier would require proportionately less reserve equipment capacity against fluctuation in demand.

- Large scale may enable the use of more specialized vehicles, and more effective management systems. Also, there are possible economies in the maintenance and servicing of large fleets.

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[6] This is not necessarily true for a multiple-output case. See Chapter Four, below, for a full discussion of this problem.

[7] A good review of these arguments can be found in Chow (1978), pp. 53-58.

The recent merger movement in the trucking industry has lent considerable support to these viewpoints. As a matter of fact, the effects from the demand side may also contribute to the mergers and concentration in the industry. As indicated by LaMond (1980), "large firms serving many points possess service and marketing advantages over small firms. Interviews with shippers reveal that they have a strong preference for minimizing the number of carriers they deal with, and that they do so by selecting carriers that provide the greatest route coverage. If so, the marketing advantages of large firms compared with smaller competitors would, in the absence of regulation, lead to still further increases in concentration in the general-freight-carrier industry."

On the other hand, it has been argued that there is nothing inherent in the structure of technology that would indicate the existence of economies of scale. The threshold costs and the costs of providing additional capacity are in general sufficiently low that they do not seem likely to provide barriers to entry. Furthermore, trucking capacity, in terms of vehicles and terminals, can be increased marginally and continuously without difficulty; and trucking capacity can easily be transferred between segments of the network. Thus, the observed cost advantages of large carriers are probably not economies of scale due to large output, but rather economies of scale due to network operations. Moreover, since the operating rights are under the control of regulation, it can be argued that the observed returns to scale are due to regulation, rather than being inherent in the technology.

To understand fully the nature of returns to scale within the general-freight trucking industry, it is necessary to distinguish three different but related dimensions: economies of large output, economies of network configuration, and economies of network operation. Each will be discussed below.

Economies of large output involve the conventional concept of scale economies. For a given type of trucking service at a given origin-destination market, there will be economies of large output if large output has cost advantages over smaller output (see Figure 2.6a). Economies of network configuration refer to cost advantages that would exist due to better arrangement in links and terminals. An extreme case, which is useful to demonstrate the concept of economies of network configuration, is given in Figure (2.6b). In the example given on the right-hand side, corridors are independent of each other; thus service at each corridor will be produced independently, implying a nonjoint production process. By contrast, in the example given in the left-hand side, the corridors are linked, implying that the carrier is likely to have cost advantages since its network configuration provides a basis for a joint production. In addition, cost advantages in the trucking industry could also be achieved through better network operations. For a given network with the same level of demand between origin points and destination points, better operating strategies and equipment utilization will result in significant cost savings (see Figure 2.6c).

The concepts of network configuration and network operation are analogous to the concepts of market extensiveness and intensiveness as suggested by Lawrence (1976).[8] Lawrence defines market extensiveness as the geographical

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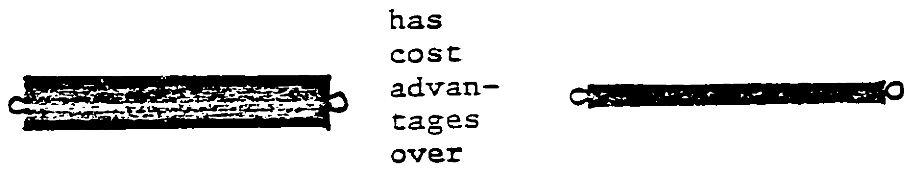
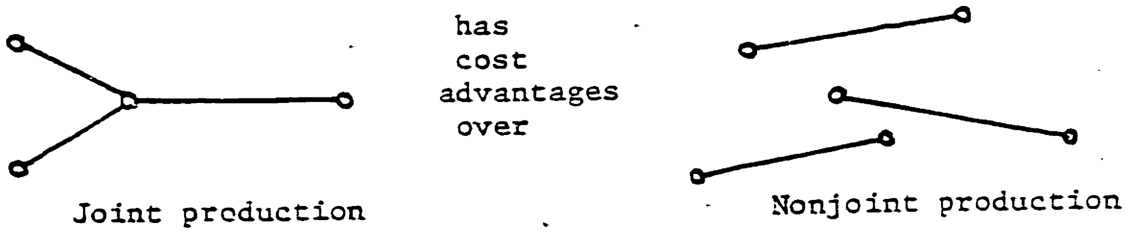
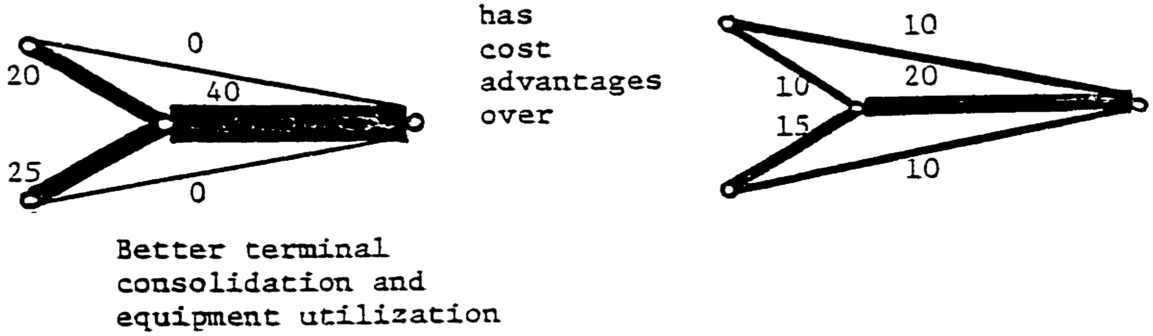
[8] A review of Lawrence's study can be found in Chapter Three, Section I, below.



a. Economies of larger output



b. Economies of network configuration



c. Economies of network operation

Figure 2.6 Economies that could exist in trucking operations dispersion of point coverage of a network, while market intensiveness (density) as the share of market that a carrier has in a given geographical territory. However, network configuration concerns not only the coverage of a network, but also the connectivities between the nodes of a network. Network operation concerns not only the traffic density, but also the routing of traffic through a network. Both economies of network configuration and network operation, or economies of extensiveness and intensiveness, can be referred to as <u>economies of scope</u> due to spatial location of a network.

For purposes of policy-making it is of crucial importance to investigate the nature of scale economies of the general-freight trucking industry in terms of the above-mentioned three dimensions. Under current regulation, network configuration of a regular-route common carrier can be altered by applying for new route authorities, or through merger and acquisition. For regular-route authorities, where opposition to the granting of new authorities by carriers already serving the market is severe, the easiest way to acquire a new authority is to buy from, or merge with, someone who already holds it. Thus, if common carriers of general commodities exhibited significant economies of network configuration, but had no indication of the existence of marked economies of network operation or of large output, one could conclude that there would be no inherent returns to scale and that the observed merger movement was due to regulatory restrictions on operating rights. In contrast, if the carriers were characterized by strong economies of network operation and of large output, but showed no evidence of the existence of economies of network configuration, one could conclude that there were returns to scale and the observed cost advantages resulting from large firm size were inherent in the underlying technology of trucking operations.

While it is useful to distinguish the possible cost advantages in terms of the above dimensions, it is difficult to observe them separately in an empirical analysis. The ideal way to observe the existence of economies of large output is to investigate the carriers that serve only one origin-destination market. Unfortunately, trucking firms usually utilize a large and dispersed network. The economies of large output, of network configuration, and of network operation tend to be interrelated and difficult to distinguish from each other, if such economies exist. However, this does indicate that the nature of trucking technology can never be understood if network effects on trucking costs are not considered. Moreover, it suggests that one would be more likely to learn the true technology of trucking operations if an empirical analysis were carried out at a more disaggregate level with respect to networks. Thus the principal goal of this research is to develop measures of network configuration and utilization and to utilize these measures in an analysis of trucking costs.

CHAPTER THREE

REVIEW OF PREVIOUS STUDIES OF TRUCKING TECHNOLOGY

I. Early Studies

A. Review

The earliest major study of the U.S. trucking technology was the motor-carrier mergers study by Adams and Hendry (1956).[1] They concluded that although concentration of the industry was increasing through mergers, such an increase could not be justified on a cost basis. This conclusion was based on a number of cost studies, primarily those of Roberts (1956) and Nelson (1956).

Roberts investigated the influence of firm size on costs of common carriers of general commodities in the Central Territory. She examined the relationship between average cost per vehicle-mile and the following variables: average length of haul, percent of truckload traffic, and vehicle-mile per route-mile. Using a cross-tabulation analysis, she concluded that small firms were generally as efficient as large ones, with small firms having comparable cost patterns to those of large carriers when they had similar route characteristics.

Nelson also utilized cross-tabulation to examine the effects of length of haul and average load on average cost per vehicle-mile and average cost per ton-mile. He concluded that the size of firm bears little relation to operating cost.

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[1] See U.S. Senate, Select Small Business Committee (1956).

Meyer, Peck, Stenason and Zwick (1959) estimated one of the first statistical cost functions for the trucking industry, using the following relationship:

$$C = 192.5 + 42.6 \log AVSIZE + (336 - 0.041 \log AVSIZE)ALH \qquad (3.1)$$

where: C = average cost in cents per hundred pounds

$AVSIZE$ = average shipment size in hundred pounds

ALH = average length of haul in miles

The inference of this equation is that average motor carrier costs vary markedly with shipment size and length of haul. Total unit costs decline with length of haul because of the distribution of terminal expenses over a higher number of ton-miles.

Emery (1965) surveyed 233 Class I and Class II Middle Atlantic motor carriers. The carriers were grouped into seven categories, graded on operating revenues. He found that operating expenses per ton-mile decreased significantly with firm size, providing evidence for the existence of scale economies within this industry.

Warner (1965) estimated a series of cost functions for Class I common carriers. He postulated the following log-linear cost function:

$$\log C = b_0 + b_1 \log NS + b_2 \log AVSIZE + b_3 \log ALH \qquad (3.2)$$

where: C = total costs

NS = output, defined as number of shipments

$AVSIZE$ = average shipment size

ALH = average length of haul

The estimated value of the b_1 coefficient indicated the presence of some economies of scale, but the economies were not overpowering. His conclusions are not comparable to those presented in other studies, however, because he used number of shipments as the measure of output.

Koshal (1972) estimated a simple linear cost function as $C = b_0 + b_1 y$, where C is costs per kilometer and y is output measured as truck kilometers. His results also suggested the existence of returns to scale in the Indian motor carriers.

Another study was done by Ladenson and Stoga (1974). They estimated the following production function using a Cobb-Douglas functional form for the common carriers of general commodities:

$$\log \frac{Y}{L} = \log A + \alpha \log \frac{K}{L} + \gamma \log L$$

$$\log \frac{Y}{K} = \log A + \beta \log \frac{L}{K} + \gamma \log K \qquad (3.3)$$

where Y is output; K and L are capital and labor inputs, respectively, and γ equals $(\alpha + \beta - 1)$; thus a significance test on the estimate of γ provides a test for the existence of returns to scale within the industry. They specified the variables to be firm-size-specific in order to investigate the scale economies of size of firm. Their estimation results indicated that larger firms seemed subject to increasing returns to scale. This agrees with Dicer's (1971) conjectures that young firms encounter numerous problems associated with growth but that after a certain point has been reached, these problems cease to exist. He suggested that the optimum size would seem to be greater than the current size of the largest carrier.

Lawrence (1976) provided additional evidence of economies of scale in the trucking industry. He argued that the cost advantages of LTL operations could come from either market intensiveness or market extensiveness, or both. The share of market that a carrier has in a given geographical territory was referred to as market intensiveness, or density. Market extensiveness is the geographical dispersion of point coverage. Although both extensiveness and intensiveness could give rise to economies in operation, intensiveness was the more important of the two. He then suggested that carriers with substantially more market extensiveness than intensiveness are operating with significant "excess capacity." A carrier with excess capacity was described as getting fewer shipments per pick-up and delivery (PUD) stop, running longer distances between PUD stops, and rehandling a higher percentage of shipments at breakbulk facilities than would be true if its market extensiveness and intensiveness were better balanced.

Lawrence argued that earlier studies on trucking costs were not adequate due to the reason that large and small carriers have not been analyzed separately. Operating characteristics are widely diverse among the smallest carriers, all of which bear little comparability to the large, long-distance carriers. Thus, he divided the Class I general-freight carriers into five groups by revenue size in dollars and average length of haul. He estimated profit, revenue and expense functions for carriers in each group using log-linear regression models. The explanatory variables were total tonnage, average length of haul, average load per vehicle, the ratio LTL tonnage/total tonnage, and average tons per LTL shipment. He included also some variables to measure market extensivness, market intensiveness, and large city cost effect. The variable for market intensiveness was average revenue per terminal divided by the average metropolitan population per terminal. The variable for market extensiveness was number of terminals operated by each carrier. His estimation results suggested that there are significant increasing returns to scale for almost all sizes of trucking firms, especially for the largest ones. Large firms were found to be more profitable than small firms, all other things equal, in the LTL general-freight motor carrier industry. And, expenses were found to rise less rapidly than output, all other things equal.

Ayala-Oramas (1975) utilized a set of simultaneous equations to explore the nature of economies of scale of the regulated trucking industry. He argued that a single equation of the cost function is likely to give biased estimates because of the presence of transient components in the observed values of cost and output data, the effects of unobserved differences in the utilization of produced transportation capacity, the aggregation of data over markets and types of service, etc. Arguing that most estimates of the coefficients indicating returns to scale tend to be biased in the direction of increasing returns, he suggested the following structural cost model:

$$\begin{aligned} C &= \alpha f^{*} + \beta q^{*} + p\gamma + u \\ f^{*} &= x\delta + v \\ q &= q^{*} + w \end{aligned} \tag{3.4}$$

where: C = cost per ton-mile

f^{*} = unobserved level of utilization of produced transportation capacity

q^{*} = unobserved true long-run output

q = observed revenue ton-miles

p = a vector of other cost-related independent variables

x = a vector of capacity-related independent variables

u, v, w are disturbances

all variables are in logarithms

Making the appropriate substitution, the relationship between observed variables becomes:

$$
\begin{aligned}
C &= \alpha x \delta + \beta q + p\gamma + u + \alpha v - \beta w \\
&= x\pi + \beta q + p\gamma + \omega \qquad (3.5)
\end{aligned}
$$

where $\pi = \alpha\delta$, and $\omega = u + \alpha v - \beta w$. He estimated Eq. (3.5) using an instrument-variable method. The RHS variables include ton-miles, average length of haul, average load per truck, percent TL traffic, average shipment size, percent of miles in owned vehicles, average compensation per worker per year, and miles per power unit. He concluded that there is no trace left of economies or diseconomies of scale after accounting for differences resulting from uneven utilization levels. Any observed economies of scale in utilization are due to the relationship bewteen the scale of operations and the characteristics of routes and shipments contributing to higher load factors.

Koenker (1977) estimated a cost function based on a time-series/cross sectional sample of general-freight carriers in the Central Region. He was interested in examining the optimal size of trucking firms and the costs of adjustment that are incurred by firms in responding to unanticipated short-run fluctuations in output level. He postulated a partial adjustment model using average length of haul (ALH), average load (AVLOAD) and ton-miles (y) as explanatory variables in the following manner:

$$\ell n\ C_{ft} = A_t + \gamma\ \ell n(\frac{y_t}{y_{t-1}}) + \alpha_o\ \ell n\ y_{t-1} + \alpha_1(\ell n\ y_{t-1})^2 + \beta_1\ \ell n\ ALH$$
$$+ \beta_2\ \ell n\ AVLOAD \qquad (3.6)$$

where C is variable costs, f is the subscript for carriers, t is the subscript for time, and the other variables have their previous meanings. The short-run cost elasticity can then be measured by the parameter γ which gives the percent change in cost resulting from a one-percent change in the proportion of current output which was unanticipated. Furthermore, Koenker allowed the short-run cost elasticity to be asymmetric with respect to over- and under-estimates of output by specifying $\ell n(y_t/y_{y-1})$ into two variables:

$$\gamma\ \ell n(\frac{y_t}{y_{t-1}}) = \gamma_1\ \ell n(\frac{y_t}{y_{t-1}})_1 + \gamma_2\ \ell n(\frac{y_t}{y_{t-1}})_2 \qquad (3.7)$$

where $\ell n(\frac{y_t}{y_{t-1}})_1 = \ell n(\frac{y_t}{y_{t-1}})$ if $y_t > y_{t-1}$; $= 0$ otherwise

$\ell n(\frac{y_t}{y_{t-1}})_2 = \ell n(\frac{y_t}{y_{t-1}})$ if $y_t < y_{t-1}$; $= 0$ otherwise

Thus a point estimate of the long-run cost elasticity is given by $(\hat{\alpha}_0 + 2\hat{\alpha}_1 y)$; and a point estimate of optimal firm size is given by $\exp((1-\hat{\alpha}_0)/2\hat{\alpha}_1)$. Koenker's analysis indicated that the industry is dominated by firms which are larger than estimated optimal size. Moreover, his estimate indicates that average cost falls dramatically as length of haul and size of load are increased. He then concluded from these findings that the ICC's loose-merger, tight-entry regulatory policies have produced a steady shift in the size distrubution of firms and a rapid decline in the number of firms in the industry. The main effect of these increases in scale of operations would be to increase the amount of long-haul, heavy-load traffic that is carried by trucks. Thus mergers between trucking firms exacerbate the possible misallocation of traffic between truck and rail.

Chow (1978) estimated a series of log-linear regression models to study the costs of general-freight carriers using the specification of the cost function developed by Warner. He stratified the industry into segments by size of revenue, average length of haul and average shipment weight to avoid the restriction of constant elasticity which is imposed by Warner's formulation. His estimation results indicated that short-haul, small-sized firms carrying small shipment sizes exhibit increasing returns to scale, with the tendency toward scale economies increasing as the length of haul and size of firm fall. However, his results suggested an absence of scale economies in the large, long-haul carriers. Chow also estimated the same models with additional regional dummy variables. These dummy variables were significant for the short-haul carriers but not for the long-haul carriers.

B. Fundamental Problems of Conventional Studies

There are two fundamental problems associated with these earlier studies of trucking technology. The first problem comes from the measure of trucking output. Although it has been recognized that trucking output is not homogeneous, but differs with product mix and product qualities, these considerations have not been fully taken into account in most empirical studies.

The second problem associated with these studies is related to the specification of the cost funciton. All of the econometric studies discussed above involve the problem of missing variables. For example, factor prices have not been included in the specification of these cost functions, although economic theory indicates that cost is a function of outputs and factor prices. Thus by omitting factor prices as explicit arguments in the cost function, these studies implicitly assume that these costs must be constant across all observations. However, given the disparity among the operations of most firms and the types of factors utilized, such an assumption seems questionable.[2]

Another problem arises because the majority of these early studies has enforced a priori restrictions regarding input-output separability in their model specifications. In specifying a cost function as $C = f(Y)g(W)$ where C is cost, Y is a vector of outputs and W a vector of factor prices, the assumption of input-output separability has been imposed.[3] A technology is called separable or homothetic if relative factor intensities are independent of the output level of mix. In the single-output case, homothetic production implies that factor isoquants are radial blowups of the unit isoquant and do not change shape as output increases (see Figure 3.1). These assumptions are severely restric-

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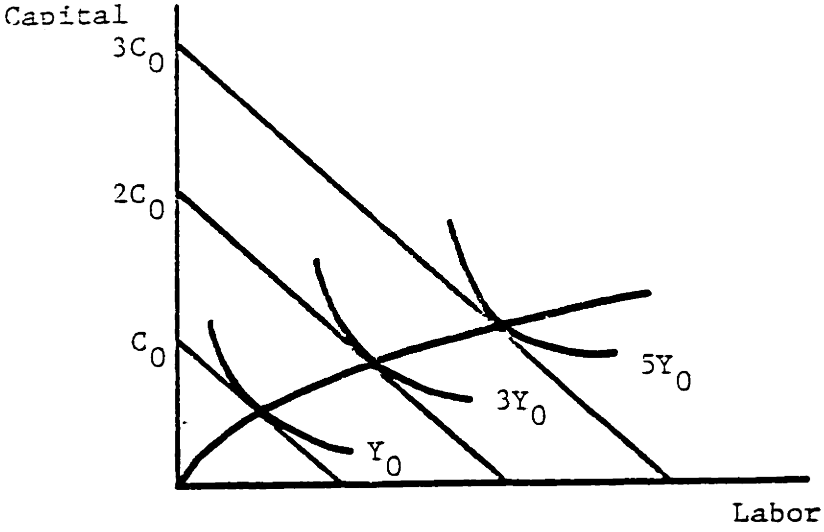
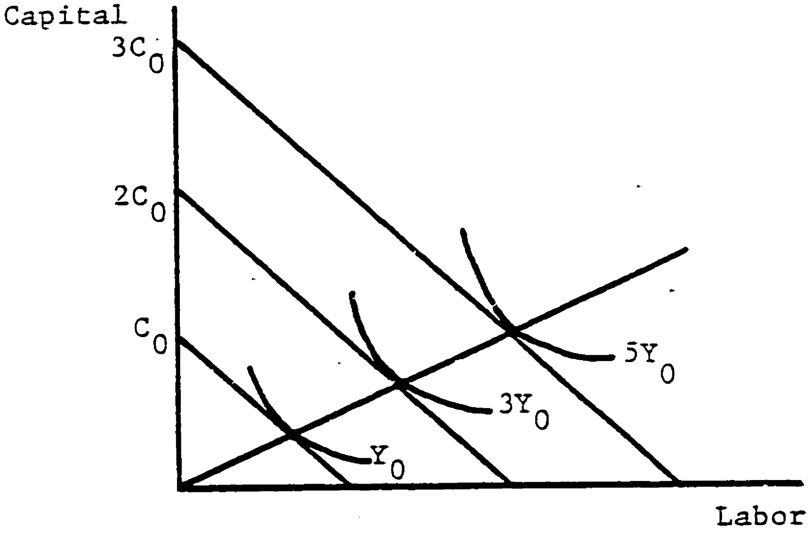
[2] Basically the problem is one of aggregation. With perfect factor markets, all firms should face the same prices for any given factor. If, however, the firms employ different operations and use different amounts of each factor, then these differences should show up in aggregate factor payments. Thus if a sufficiently fine breakdown of factor payments existed, it might be acceptable to treat these as being constant across firms. Since, however, observed factor payments reflect an aggregate of different types of each factor, it is highly unlikely that these aggregates will be constant across fi

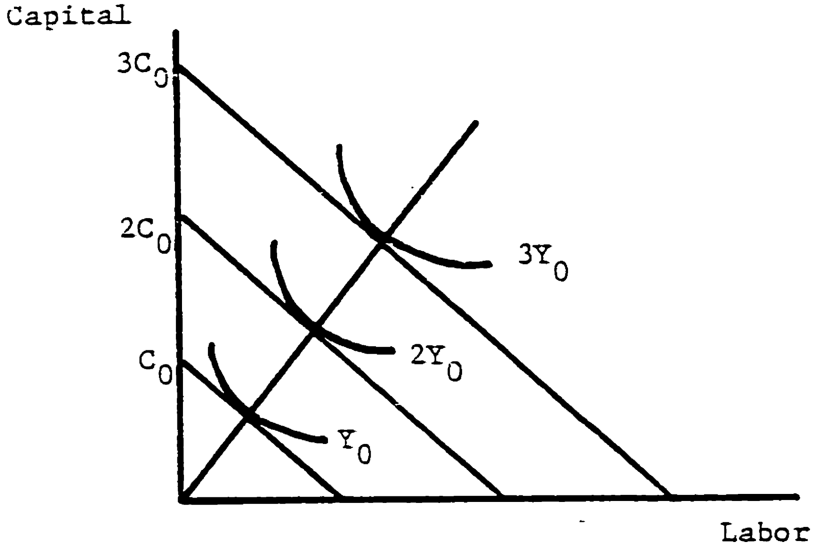
[3] See Hall (1973) for details.



(a) Nonhomothetic Production, Increasing Returns to Scale



(b) Homothetic Production, Increasing Returns to Scale



(c) Homothetic Production, Constant Returns to Scale

Figure 3.1 Homothetic and Nonhomothetic Productions tive, and efforts to describe technology by a separable production function, such as the Cobb-Douglas function, may lead to seriously biased estimates.

II. Recent Studies

Attempts have recently been made to estimate general cost functions using flexible functional forms for the trucking industry, which have also tried to take the heterogeneity of trucking output in single-output production into account. In one of the first of these studies, Spady and Friedlaender (1978) tried to treat effective trucking output as a function of a generic measure of physical output and its qualities. Thus the cost function was postulated to be:

$$C = C[\psi(Y,Q),W] \tag{3.8}$$

where: C = total costs

Y = physical output in ton-miles

Q = quality variables, including average length of haul, average shipment size, percent LTL traffic, and insurance cost per ton-mile

$\psi(Y,Q) = Y\cdot\phi(Q)$ = hedonically adjusted output

W = a vector of factor prices

Quality variables were used to adjust physical output of ton-miles, and both of these variables were assumed to be exogenous and beyond the control of the trucking firm. Using a translog approximation, the cost function and its associated factor share equations, implied by Shephard's lemma were estimated for general-commodity carriers in the Official Territory in 1972. Spady and Friedlaender concluded that there were substantial nonhomotheticities in the structure of trucking firms' production. Consequently, any attempt to model their technology by the use of a homothetic cost or production function (such as the Cobb-Douglas or the CES) suffers from serious misspecification. They also found that the operating characteristics such as length of haul, size of load and share of LTL traffic have a significant effect upon costs, which tends to dominate the pure size effect. In particular, evidence of increasing returns to scale exists when ton-miles is used as a single output measure, but fails to exist when output is adjusted for quality differentials.

Weak separability was still imposed in the Spady-Friedlaender cost specification, since service characteristics, Q, were assumed to have no effect on factor intensities.[4] Later studies have tried to remove these restrictions by specifying the cost function as:[5]

$$C = C[Y,W;T(Q)] \tag{3.9}$$

where: C = total costs

Y = physical output in ton-miles

W = a vector of factor prices

T(Q) = a vector of operating characteristics.

In this specification, operating characteristics such as length of haul and size of load were treated as service conditions in production that are determined by operating rights and the necessity to provide common-

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[4] This is somewhat restrictive, since short-haul, small-shipment LTL service is likely to be more labor-intensive.

[5] See Spady (1978), Wang Chiang (1979), Friedlaender, Spady and Wang Chiang (1981), and Friedlaender and Spady (1981).

carrier service.

Wang Chiang (1979), and Friedlaender, Spady, and Wang Chiang (1981) used the cost function specification of Eq. (3.9) to investigate the regional differences in the structure of cost and technology of the trucking industry. The general-commodity trucking market is geographically segmented into three groups: regional carriers in the Official Territory (northeastern regional carriers representing short-haul, regional carriers), regional carriers in the rest of the country (representing intermediate-haul, regional carriers), and interregional and transcontinental carriers (representing long-haul, interregional carriers). Both studies used four factor prices (price of labor, fuel, capital, and purchased transportation) and six operating characteristics variables (ALH (average length of haul), AVLOAD (average load per vehicle), LTL (percent of freight in LTL lots), AVSIZE (average shipment size), INSUR (average insurance cost per ton-mile), and TERMINAL (ton-miles per terminal)) to specify their cost functions. Insurance cost was used to measure the commodity composition of output, since it reflects differences in fragility and costs of special handling. Using translog approximation to Eq. (3.9) yielded:[6]

$$\ln C = \alpha_0 + \sum_i \alpha_i \ln w_i + \sum_j \beta_j \ln t_j + \gamma_y \ln y$$

$$+ 1/2 \sum_i \sum_\ell A_{i\ell} \ln w_i \ln w_\ell + \sum_i \sum_j B_{ij} \ln w_i \ln t_j$$

---

[6] Note that all variables were measured as deviations from the sample mean.

$$+ \sum_i C_{iy} \ln w_i \ln y + 1/2 \sum_j \sum_m D_{jm} \ln t_j \ln t_m$$

$$+ \sum_j E_{jy} \ln t_j \ln y + 1/2 F_{YY} (\ln Y)^2 \qquad (3.10)$$

where w_i's are factor prices, and t_i's are operating characteristics.

Their estimation results again indicated that the technology of general-freight motor carriers is nonhomothetic. Moreover, estimated coefficients indicated also that the assumption of quality separability, which has been utilized in Spady-Friedlaender's formulation, should be rejected. Operating characteristics such as ALH, AVLOAD and LTL do have important effects on factor utilization. Moreover, these studies found that the technologies and cost structures of the three geographaically segmented carriers were different. Statistic testing rejected not only the hypothesis that the technologies were identical in all regions, but also rejected the hypothesis that regional carriers in both the Official Territory and the rest of the country face the same technology.

Since the technology is nonhomothetic and different among types of carriers, global characterizations of the relationships between costs and operating characteristics as well as between costs and output are not generally possible. Thus the relationships between costs and output generally depend upon the operating charactersitics as well as upon factor prices. In particular, their models suggested that rather substantial cost reductions could occur with increases in average length of haul, average load, or average shipment size. The elasticity of costs with respect to output, which gives a local measure of returns to scale, is given by

$$\frac{\partial \ln C}{\partial \ln y} = \gamma_y + \sum_i C_{iy} \ln w_i + \sum_j E_{jy} \ln t_j + F_{yy} \ln y \qquad (3.11)$$

Thus local returns to scale depend not only on factor prices but also on operating characteristics of the firm. The estimated coefficients of equation (3.11) in Friedlaender-Spady-Wang Chiang's study are shown in Table 3.1. At mean factor prices, operating conditions and output levels, $\partial \ln C/\partial \ln y = \gamma_y$; thus a "typical" firm with sample mean characteristics would face declining returns to scale in the Official Territory and Other regional samples and increasing returns to scale in the interregional sample. However, since no firm in the interregional sample corresponds very closely to the hypothetical firm of the sample mean, they claimed that the findings for the large, interregional carriers should not be conclusive. A close examination of the cost elasticities with respect to the output of each carrier indicated that the hypothesis of constant returns to scale cannot be rejected for the overwhelming majority of the sample. Moreover, operating characteristics were shown to have comparaitvely weak impacts on cost elasticities for the small, regional carriers but to have rather significant impacts for the large, interregional carriers.

Although the Wang Chiang (1979) and Friedlaender-Spady-Wang Chiang (1981) studies failed to reject the hypothesis that there are slight economies of scale in the large, interregional common-commodity carriers, one could not infer from their analysis whether the nature of the size-related economies comes from the scale of output, the network configuration, network operation, or some combination of these factors, since network

Table 3.1 Elasticity of Cost with Respect to Output at Mean Factor Prices, by Type of Carrier, 1972[a]

Parameter	Region Northeast	 Regional	 Interregional
γ_y	1.0864 (0.0376)	1.0759 (0.0273)	0.8969 (0.0501)
E_{1y}(ln ALH)	0.0365 (0.0504)	−0.0467 (0.0606)	−0.0932 (0.0600)
E_{2y}(ln AVLOAD)	0.0128 (0.0562)	0.1604 (0.0705)	0.2602 (0.0957)
E_{3y}(ln LTL)	0.1434 (0.0679)	0.0681 (0.0722)	−0.2664 (0.0819)
E_{4y}(ln AVSIZE)	0.0014 (0.0447)	0.0086 (0.0454)	−0.3223 (0.0868)
E_{5y}(ln INSUR)	0.0035 (0.0271)	0.0388 (0.0283)	−0.0413 (0.0581)
E_{6y}(ln TERMINAL)	—	—	0.0990 (0.0338)
F_{yy}(ln y)	0.0248 (0.0347)	0.0533 (0.0256)	−0.0880 (0.0320)

[a] Standard errors are in parentheses.

Source: Friedlaender, Spady and Wang Chiang, "Regulation and the Structure of Technology in the Trucking Industry," in Cowing and Stevenson (eds.), Productivity Measurement in Regulated Industries, Academic Press, 1981, p. 97.

effects did not enter into their analysis. Therefore, these findings are not particularly helpful in clarifying the controversy over whether the observed size-related economies in these carriers are inherent to their true technology or merely due to regulatory restrictions on operating rights.

CHAPTER FOUR

THEORIES OF MULTIPRODUCT COST FUNCTIONS

Since regulatory constraints have limited carriers' flexibility to adjust their rates in practice, and since common-commodity carriers cannot refuse to haul freight at rates established by the ICC, it is appropriate to study the technology of these carriers by means of cost functions rather than profit functions. A common carrier of general freight typically has little control over its level of output in the current regulatory environment.[1] Under these circumstances, a cost function will give the same information on the underlying technology as a production function.[2] Unfortunately, however, while the theory of the structure of technology has been well developed in the case of a single-output firm, it is less well developed for the case of the multi-output firm. Only recently has research been directed toward a characterization of the technology of multiple-output production. However, this research has not generally been utilized in empirical studies to analyze the relationships between costs and outputs in industries that produce multiple outputs.[3] Since, however, it is a basic contention

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[1] However, there is some anecdotal evidence that these carriers refuse traffic that they think would be unprofitable. Nevertheless, such behavior has never been quantified.

[2] For a good discussion of the duality theory involved see Varian (1978). For a more technical discussion see McFadden (1978).

[3] For example, Buamol (1977), Baumol, Bailey and Willig (1977), Panzar and Willig (1978), Baumol, Panzar and Willig (1979), and Willig (1979). These references are used extensively in this section. See, in addition, Baumol and Braunstein (1977) for an empirical analysis of multiple output industries

of this report that trucking is characterized by multiple outputs, this analysis will begin with a brief review of the measurement of economies of scale and of scope for a multiple-output industry.

Technology is conventionally represented by a production or transformation function, which represents a relationship between a vector of factor inputs, $X = (x_1, \ldots, x_m)$, and a vector of outputs, $Y = (y_1, \ldots, y_n)$, under certain technological conditions of production, $t = (t_1, \ldots, t_k)$ that can be defined in terms of a transformation function (McFadden, 1978).[4/] This can be written generically as:

$$T(Y,X;t) = 0 \tag{4.1}$$

By duality theory, corresponding to every production function there is an associated cost function. A general specification for a multi-product joint cost function is defined as:

$$C = (Y,W;t) \tag{4.2}$$

which solves

$$\min_{X} \sum_{i} w_i x_i \quad \text{s.t.} \quad T(Y,W;t) = 0 \tag{4.2a}$$

where $W = (w_1, w_2, \ldots, w_m)$ is a vector of factor prices. As shown in Shephard's lemma (1970), the vector of cost-minimizing factor inputs is equal to the vector of derivatives of the cost function with respect to factor prices:

$$x_i = \frac{\partial C(Y,W;t)}{\partial w_i} \quad \forall\, i \tag{4.3}$$

[4/] McFadden (1978) suggests specifying a continuum of technologies — each corresponding to a different value of the t vector — to the usual neo-classical cost function $C = C(Y,W)$.

The cost advantages of a multiple-output production can be studied from two aspects. First, to produce each individual output or several outputs with fixed proportions, a single firm may have cost advantages over two or more firms. In other words, the technology may exhibit economies of scale due to quantity of production. Since output proportions are held unchanged in this case, the problem is to analyze the curvature of the cost surface along a ray in output space.[5] The second aspect is whether a single firm obtains a cost advantage by producing an output bundle relative to many firms each of which produces a subset of that bundle at the same output level. In other words, the technology may exhibit economies of scope for simultaneous production of many products. In this case, the problem is to analyze the cross section of the cost function as output proportions vary. We will examine each of these aspects in turn.

I. Cost Behavior along a Product Ray—Economies of Scale

Average and marginal costs are traditionally used to indicate the shape of the cost curve as output quantity varies in single-output production. Average costs are said to be strictly declining at y if there exists a $\delta > 1$ such that

$$C(\lambda y, W; t)/\lambda y < (y, W; t)/y, \quad 1 < \lambda < \delta \qquad (4.4)$$
$$y > 0$$

To derive average costs for a multiple-product technology, the concept of ray-average cost is used. The basic idea is to aggregate the entire

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[5] Definition for an output-ray is given below.

output vector into a composite good through some fixed weights which are assigned to each output, and are held unchanged. Thus the output bundle varies in fixed proportions along a ray which allows one to measure the average cost as in the single-product case. Different weights assigned to the output bundle result in a different ray in the output space. Figure 4.1 illustrates the concept of ray total costs and ray average costs in the two-product case.

A multiproduct cost function has strictly decreasing ray average cost if

$$C(\lambda Y,W;t)/\lambda < C(Y,W;t) \quad , \quad 1 < \lambda \qquad (4.5)$$

for any output vector $Y \neq 0$; that is, whenever a small proportional change in outputs along a ray leads to a less-than-proportional change in total costs, decreasing ray-average costs are said to exist. A cost function is strictly output-ray concave if marginal costs of output bundles are everywhere decreasing. It can be shown that strict ray concavity and $C(0) = 0$ implies declining ray-average costs, but the reverse is not necessarily true. As in the single-output case, average costs can be declining when marginal costs are rising.

Economies of scale measure the relative change in the quantities of inptus and outputs. A technology is said to have economies of scale if a proportional increase of inputs results in a more-than-proportional increase in outputs. In terms of cost functions, a local measure (S) of the degree of multiproduct scale economies at (Y,W;t) can be defined as

$$S(Y,W;t) = \frac{C(Y,W;t)}{Y\cdot\nabla C(Y,W;t)} = \frac{C(Y,W;t)}{\sum_j y_j C_j(Y,W;t)} = 1\Bigg/\sum_j \frac{\partial \ln C(Y,W;t)}{\partial \ln y_j} \qquad 4.6)$$

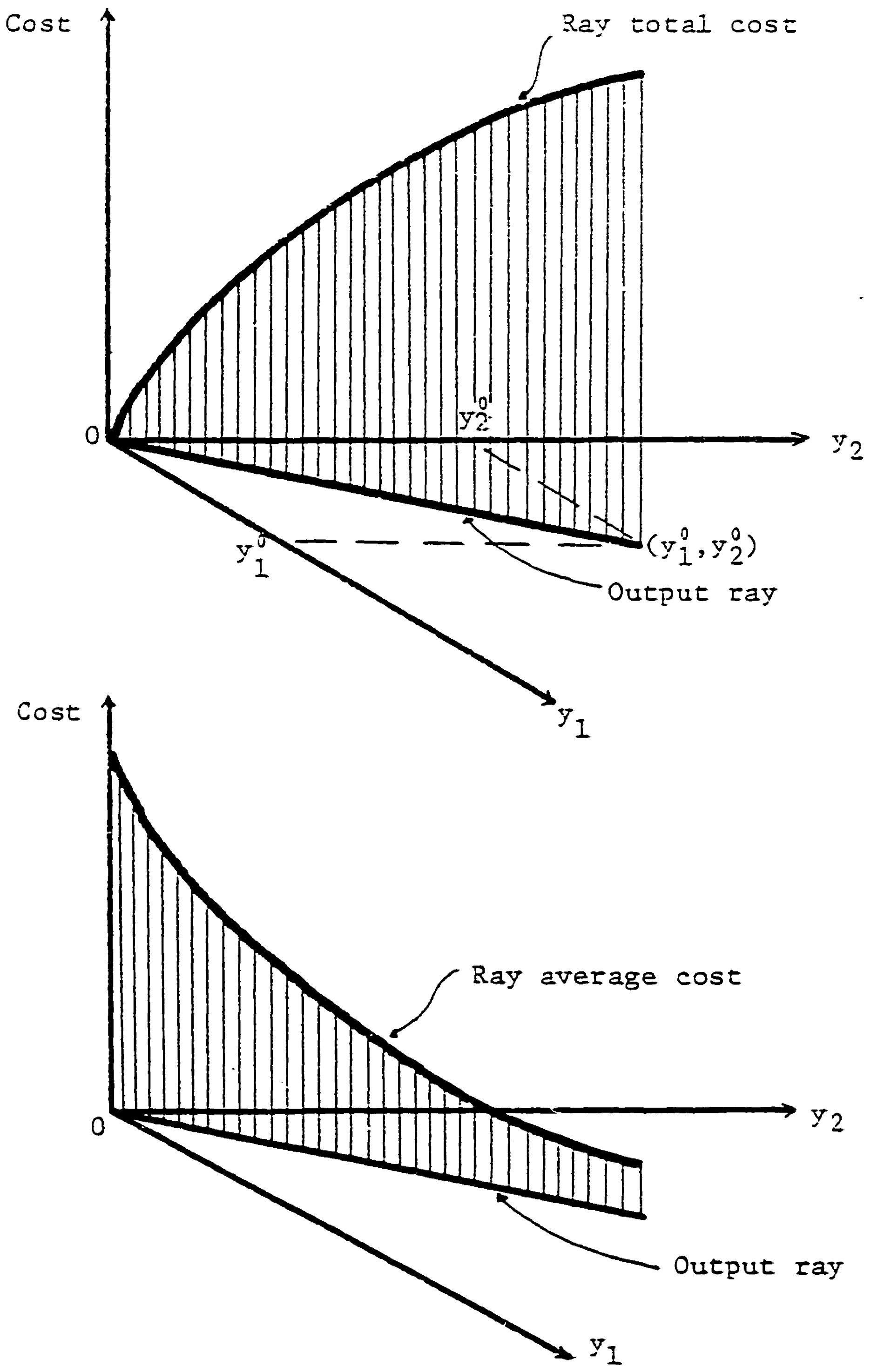

Figure 4.1 Costs along a Ray in the Two-Product Case

where $C_j = \partial C/\partial y_j$. Thus the technology exhibits increasing, constant, or decreasing returns to scale at $(Y,W;t)$ is S is greater than, equal to, or less than unity, respectively.

The concept of cost subadditivity considers the question of whether one firm can produce the output bundle at a lower cost than two or more firms. A cost function is said to be strictly and globally subadditive if for any m output vectors $Y^1(y_1^1,\ldots,y_n^1)$, $Y^2(y_1^2,\ldots,y_n^2),\ldots,Y^m(y^m,\ldots,y_n^m)$, the following holds:

$$C(Y^1 + Y^2 + \ldots + Y^m,W;t) < C(Y^1,W;t) + \ldots + C(Y^m,W;t) \tag{4.7}$$

Thus global subadditivity is a necessary and sufficient condition for natural monopoly of any output combination in a multi-product industry, for it implies that it is always cheaper for a single firm to produce any combination of outputs which are supplied to the market. Strict subadditivity along a ray means that a single firm can produce a given amount at a lower cost than many firms if outputs are produced in fixed proportions. In the transportation market, for example, global subadditivity implies that a carrier serving both short-haul and long-haul corridors has cost advantages over two or more carriers serving either short-haul or long-haul corridors exclusively. Ray subadditivity also implies that one carrier has a cost advantage over two or more carriers each serving short-haul and long-haul corridors, at some fixed proportions.

It is important to note that both economies of scale and ray concavity imply declining ray-average cost and that declining ray-average cost implies ray subadditivity; but the reverse is not necessarily true. Therefore, scale economies, declining ray-average cost, or ray concavity are sufficient but not necessary conditions for subadditivity along a ray. The above conclusions hold also in the single-output case. To see this, some counter examples would be helpful. Figure 4.2 gives an example of a single-output firm in which the average cost is strictly declining but returns to scale are not globally increasing. At output level $y = 1$, the technology presents constant returns to scale since average costs equal marginal costs. Figure 4.3 presents a case in which the cost function is characterized by strict ray subadditivity but it is not ray concave throughout, and ray-average cost is not declining throughout.[6/]

One implication of the above ray behavior is that the conventional approach of diagnosing the existence of natural monopoly by using scale economies or decreasing average cost in a single-output technology, or in a multiple-output technology where the output vector is aggregated through hedonic functions, may not be appropriate if the firm's production is characterized by multiple outputs.

II. Cost Behavior as Output Proportions Vary

As indicated earlier, ray subadditivity does not necessarily imply natural monopoly. Cost subadditivity should hold globally to ensure a natural monopoly. Ray subadditivity is equivalent to multi-product natural monopoly only if firms are constrained to produce their outputs in precisely the same proportions — a condition which is, in general, unrealistic. Thus, it is also necessary to study the behavior of costs as

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[6/] These examples are taken from Baumol, Panzar and Willig (1979), and Baumol (1977).

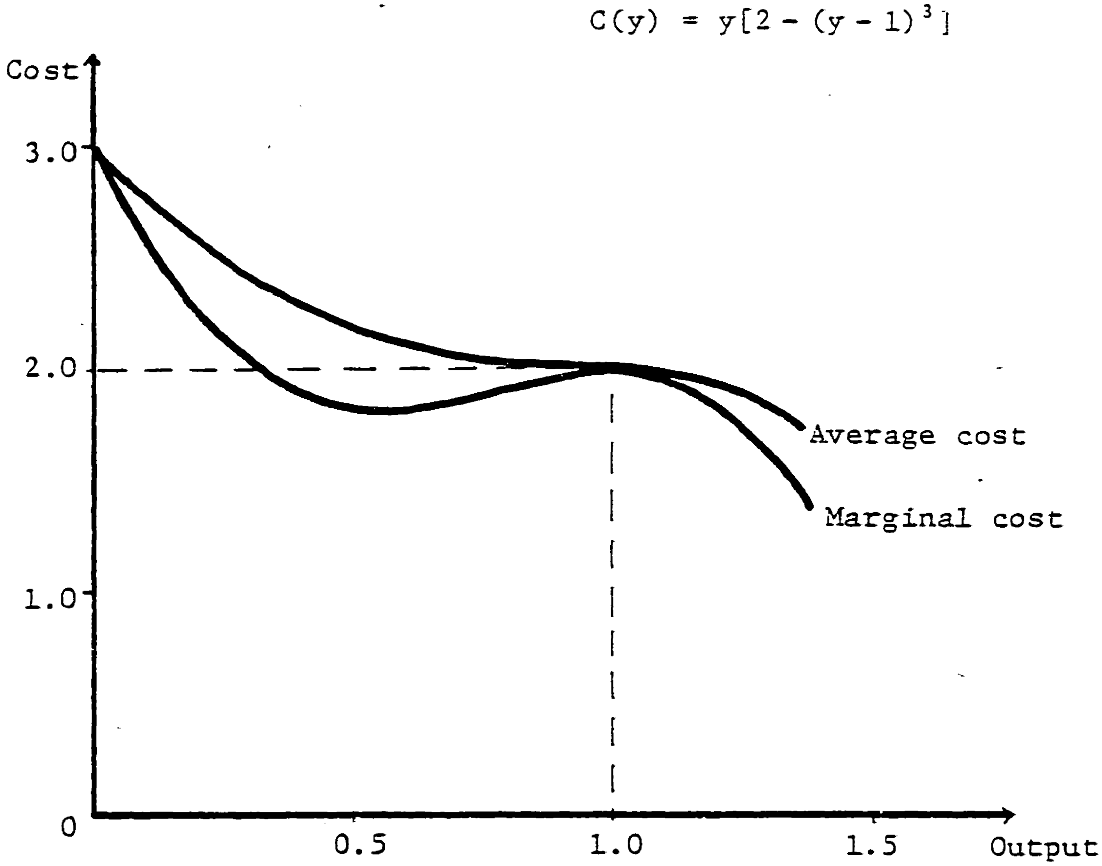
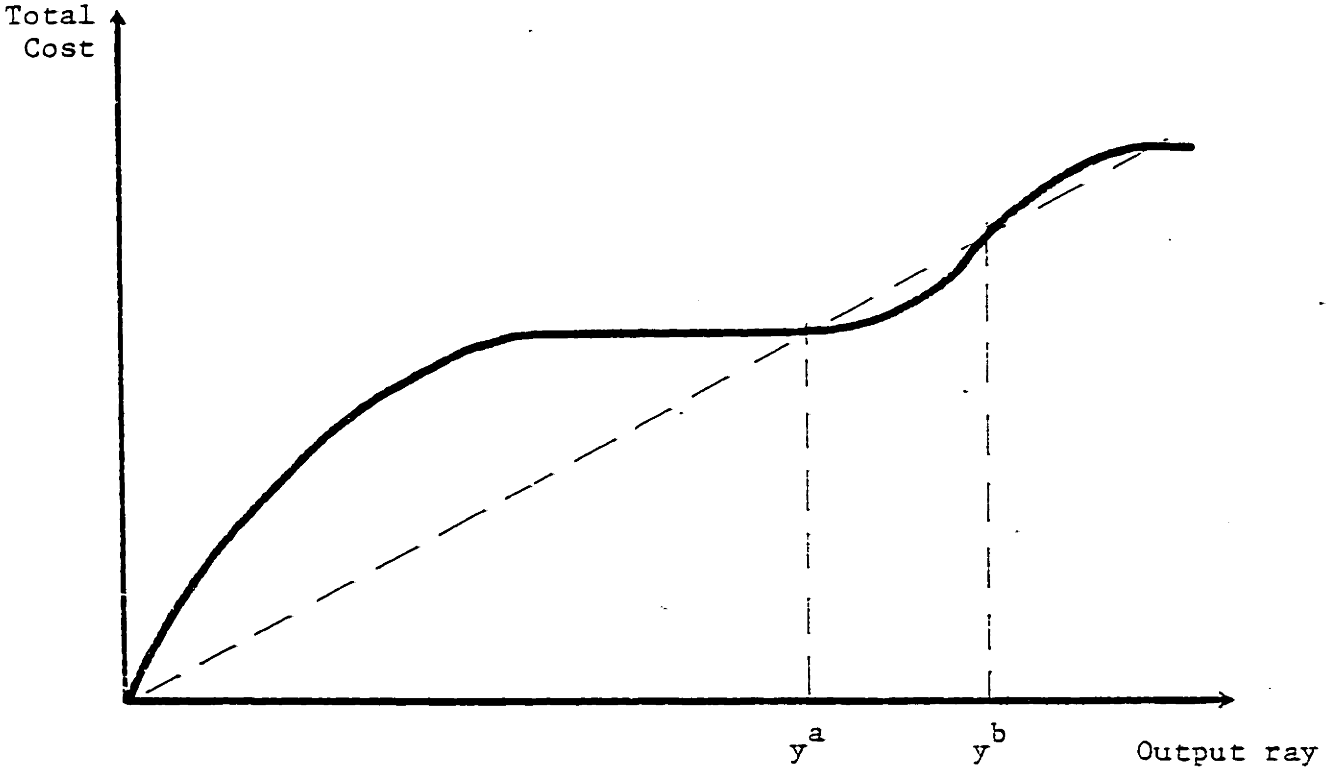


Figure 4.2 Declining Average Cost Does Not Imply Scale Economies: An Example

Source: Baumol, Panzar and Willig (1979), p. 15.



Average Cost at y^b = Average Cost at y^a

Marginal Cost at y^b > Marginal Cost at y^a

Figure 4.3 Ray Subadditivity Does Not Imply Ray Concavity or RAC Declining: An Example

Source: Baumol (1977).

output proportions vary in order to be able to test for natural monopoly.

The first concept which is useful in this context is incremental cost. The incremental costs of product i are the additional costs incurred by the firm to produce the given level of output i, while the quantitites of other products are held constant. Mathematically, this is given by:

$$IC_i(Y,W;t) = C(Y,W;t) - C(Y_{-i},W;t) \tag{4.8}$$

where: $IC_i(Y,W;t)$ = the incremental cost of y_i at Y

Y_{-i} = output vector Y in which $y_i = 0$

Naturally, average incremental costs of y_i (AIC_i) can be defined as

$$AIC_i(Y,W;t) = IC_i(Y,W;t)/y_i \tag{4.9}$$

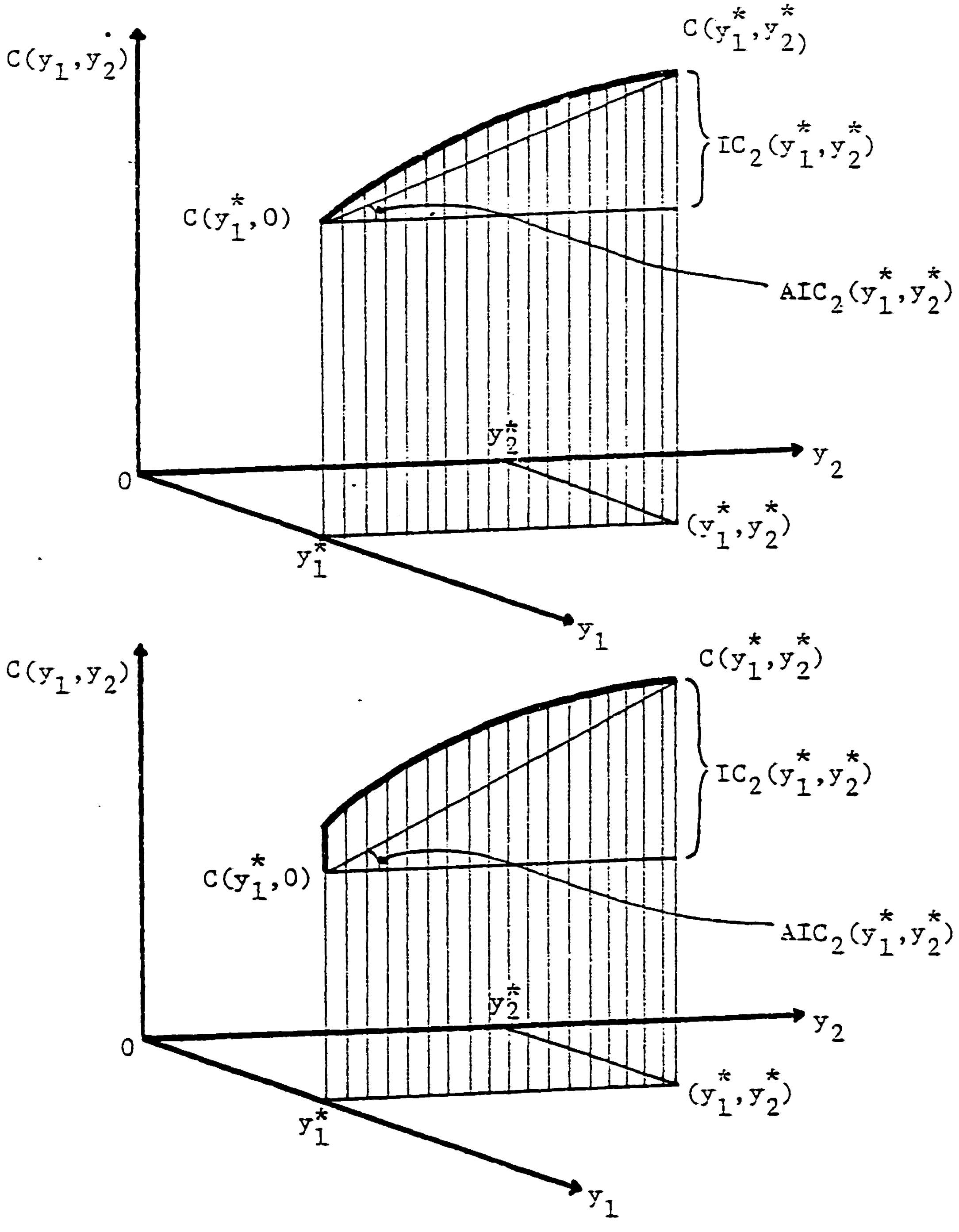
Note that incremental costs can be either positive, zero or negative. The concept of incremental cost can be easily extended to a subset of products. Figure 4.4 illustrates the concept of incremental cost in a two-product case.

The concept of incremental cost is useful in measuring scale economies with respect to a specific output. Product-specific scale economies (S_i) which measure the degree of returns to scale of output i at (Y,W;t), can be defined as:

$$S_i(Y,W;t) = \frac{IC_i(Y,W;t)}{y_i C_i(Y,W;t)} = \frac{AIC_i(Y,W;t)}{C_i(Y,W;t)} \tag{4.10}$$

where $C_i \equiv \partial C/\partial y_i$ and the other variables have their previous meanings. It can be shown that the relationship between the traditional, multiproduct scale economies which are defined by Eq. (4.6) and product-specific scale

Case I: No Fixed Cost of Beginning Production of y_2



Case II: With Fixed Cost of Beginning Production of y_2

Figure 4.4 Incremental Costs in a Two-Product Technology economies, which are defined by Eq. (4.10) are given as follows:

$$S(Y,W;t) = \frac{\sum_i \alpha_i S_i(Y,W;t)}{\sum_i \frac{IC_i(Y,W;t)}{C(Y,W;t)}} \tag{4.11}$$

where $\alpha_i = y_i C_i(Y,W;t)/\sum_j y_j C_j(Y,W;t)$, $\sum_i \alpha_i = 1$

Thus S is a weighted average of S_i's if the denominator is equal to unity, i.e., the sum of incremental costs of each product is equal to total costs.

A basic policy issue with respect to multiproduct enterprises is whether there are cost savings associated with the simultaneous production of many products, as opposed to a number of specialized firms each producing products in isolation. In other words, an important question is whether economies can be achieved through the scope of the firm's operations. This can be measured by the degree of economies of scope. In the two-output case, there are economies of scope over $Y = (y_1, y_2)$ if

$$C(y_1,y_2,W;t) < C(y_1,0,W;t) + C(0,y_2,W;t) \tag{4.12}$$

And the degree of scope economies, SC, is measured as[7]

$$SC(y_1,y_2,W;t) = \frac{C(y_1,0,W;t) + C(0,y_2,W;t) - C(y_1,y_2,W;t)}{C(y_1,y_2,W;t)} \tag{4.13}$$

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[7] Equations (4.12) and (4.13) can be easily extended to a more general multiproduct case. It can be shown also that economies of scope represent a restricted case of subadditivity in which output vectors are orthogonal; see Baumol (1977).

Economies of scope arise mainly from inputs that are shared or utilized jointly. The existence of economies of scope presents barriers to entry, since the greater the economies of scope, the greater the cost advantages of a firm that offers many products; hence the greater the difficulty for firms to enter and compete in a market.

Baumol, Panzar and Willig (1979) have derived an explicit relation between multiproduct economies of scale and economies of scope as follows:

$$S(Y,W;t) = \frac{\alpha_T S_T(Y,W;t) + (1-\alpha_T)S_{-T}(Y,W;t)}{1 - SC_T(Y,W;t)} \tag{4.14}$$

where T = a subset of output vector, $Y = Y_T + Y_{-T}$

$SC_T = SC_{-T}$ = economies of scope where $Y = (y_1,\ldots,y_n)$ is partitioned as Y_T and Y_{-T}

S_T = product-specific scale economies for Y_T

S_{-T} = product-specific scale economies for Y_{-T}

$$\alpha_T = \frac{\sum_{j\varepsilon T} y_j C_j(Y,W;t)}{\sum_{j\varepsilon N} y_j C_j(Y,W;t)}$$

Clearly, one can see that multiproduct economies of scale are a weighted average of product-specific scale economies if there are no economies of scope. This corroborates the conclusion indicated earlier (Eq. (4.11)), since the absence of economies of scope when partitioning Y into Y_T and Y_{-T} implies that the sum of incremental costs of producing Y_T and Y_{-T} is equal to total costs of producing Y simultaneously, i.e., $IC_T + IC_{-T} = C$. Furthermore, one can see that economies of scope in fact magnify the degree of overall scale economies through product-specific scale economies.

For example, if economies of scope are present, there is still the possibility of overall increasing returns to scale, even if product-specific returns to scale are constant or decreasing for both Y_T and Y_{-T}.

The concept of economies of scope is closely related to the conventional idea of cost complementarities. A multiproduct cost function is said to exhibit weak cost complementarities over the product set at Y if

$$\frac{\partial^2 C(\tilde{Y},W;t)}{\partial y_i \, \partial y_j} \leq 0 \ , \ i \neq j \ , \ \tilde{Y} \leq Y \qquad \forall \tilde{Y} \varepsilon [0,Y] \tag{4.15}$$

In fact, weak cost complementarities are a sufficient condition for economies of scope.

Another concept which is useful in analyzing multiproduct cost behavior is the transray cross section, i.e., the cross section of the cost hypersurface that connects points on the output axes. Figure 4.5 illustrates the concept of the transray cross section in a two-output case. Line segment AB is a hyperplane through point $Y^* = (y_1^*, y_2^*)$, and line CD is another hyperplane through the same point Y^*. Thus, there will be an infinite number of hyperplanes for a point in output space. The segment of the cost surface above a hyperplane is a so-called transray cross section. For example, line segment A'B' is the transray cross section for hyperplane AB through point Y^*. One can readily see that if the transray A'B' is convex (as shown in Figure 4.5), producing both y_1 and y_2 simultaneously will always be cheaper than producing them separately as long as outputs are along the hyperplane AB.

Mathematically, a cost function is transray convex along a hyperplane $\sum_i u_i y_i = v$, $\forall u_i > 0$, if for any vectors of outputs Y^a, Y^b on that hyperplane,

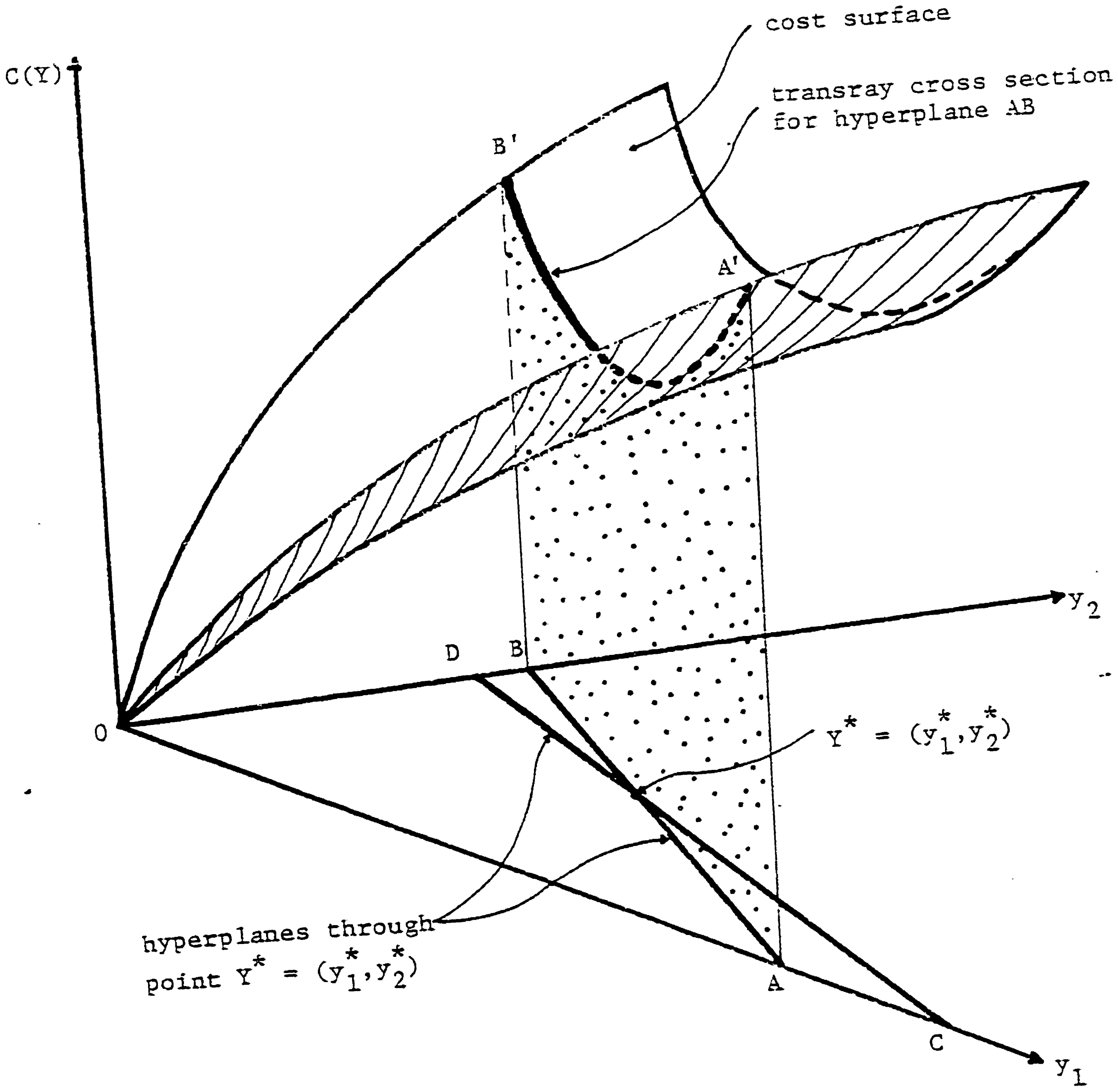

Figure 4.5 Cost Surface and Transray Cross Section in Two-Product Case

$$C[\lambda Y^a + (1-\lambda)Y^b, W; t] \leq \lambda C(Y^a, W; t) + (1-\lambda)C(Y^b, W; t) \qquad (4.16)$$

$$0 < \lambda < 1$$

Note that the cost surface may be transray convext at one point Y^* and not at another point Y^{**}. Also, the concept of transray convexity at a point requires that the condition of Eq. (4.16) is satisfied along at least one hyperplane, but not all hyperplanes, through the point.

A cost function does not exhibit transray convexity if there are product-specific fixed costs (Figure 4.6). However, Baumol, Panzar, and Willig (1979) have shown that this has not prevented us from using the concepts described so far. The cost tests can be performed on variable costs only; and under some conditions, subadditivity of the variable cost function implies subadditivity of the total cost function.

III. Tests for Natural Monopoly

The principal purpose of the above concepts is to try to provide useful tools for testing for the existence of a multiproduct natural monopoly. A necessary and sufficient condition for multiproduct natural monopoly is global subadditivity in the cost surface. Since subadditivity is a global concept, to observe empirically the existence of subadditivity at Y would require all information on costs for every possible output vector $Y' \leq Y$, which is virtually impossible in the real world. Thus one has to rely on analytically tractable concepts to detect subadditivity from estimated cost functions in a statistical way. It is thus useful at this point to review the cost behavior discussed so far which is related to subadditivity, with special emphasis on

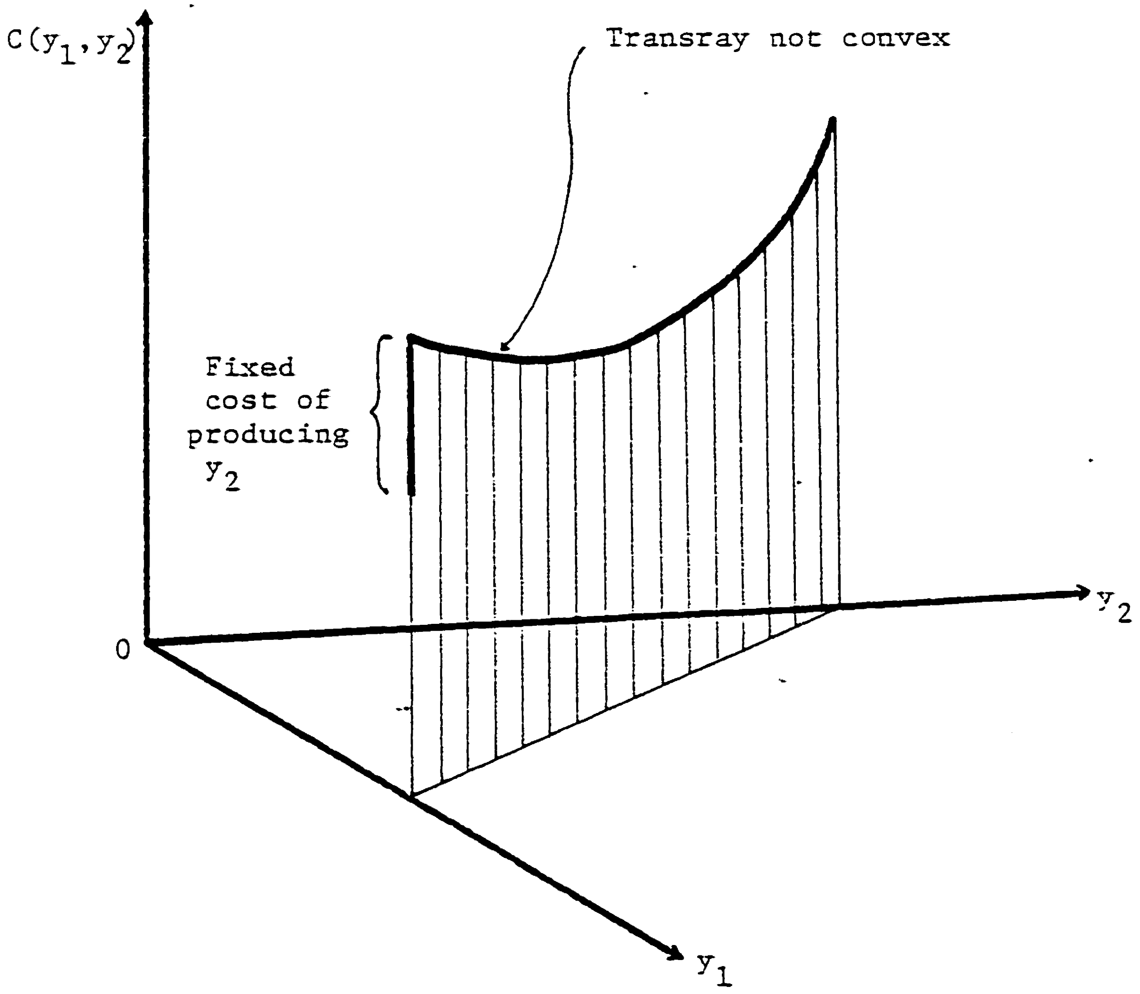

Figure 4.6 Product-Specific Fixed Costs and Transray Nonconvexity

analytical and statistical tractability.

Figure 4.7 summarizes these multiproduct cost concepts (Baumol (1978)). As we have seen, subadditivity requires the existence of economies arising from proportional expansion of the output vector along a ray as well as economies arising from product combinations along a hyperplane. The necessary and sufficient condition for economies from proportional expansion is ray subadditivity. We have mentioned that strictly decreasing ray-average cost implies ray subadditivity. There are at least two plausible ways to test whether ray-average cost is decreasing: by testing whether there are multiproduct scale economies, or, alternatively, whether the cost surface is strictly ray-concave (Figure 4.7). Both tests can be performed on statistically determined cost functions without much difficulty.

However, it is somewhat more complicated to test for the existence of economies from product combinations. We have introduced several cost concepts which are useful to indicate these economies. One of them is the concept of transray convexity. Another one is weak cost complementarity, which is a stronger condition than transray convexity. Weak cost complementarity, in general, imply transray convexity, but the reverse is not true. Moreover, since overall output convexity of the cost function always implies transray convexity, the former is also a useful tool to test for the existence of cross sectional cost advantages.[8]

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[8] Yet another concept not mentioned, which also indicates cross sectional cost advantages, is quasi-convexity. See Baumol, Panzar, and Willig (1979) for the definition of quasi-convexity and its application to subadditivity.

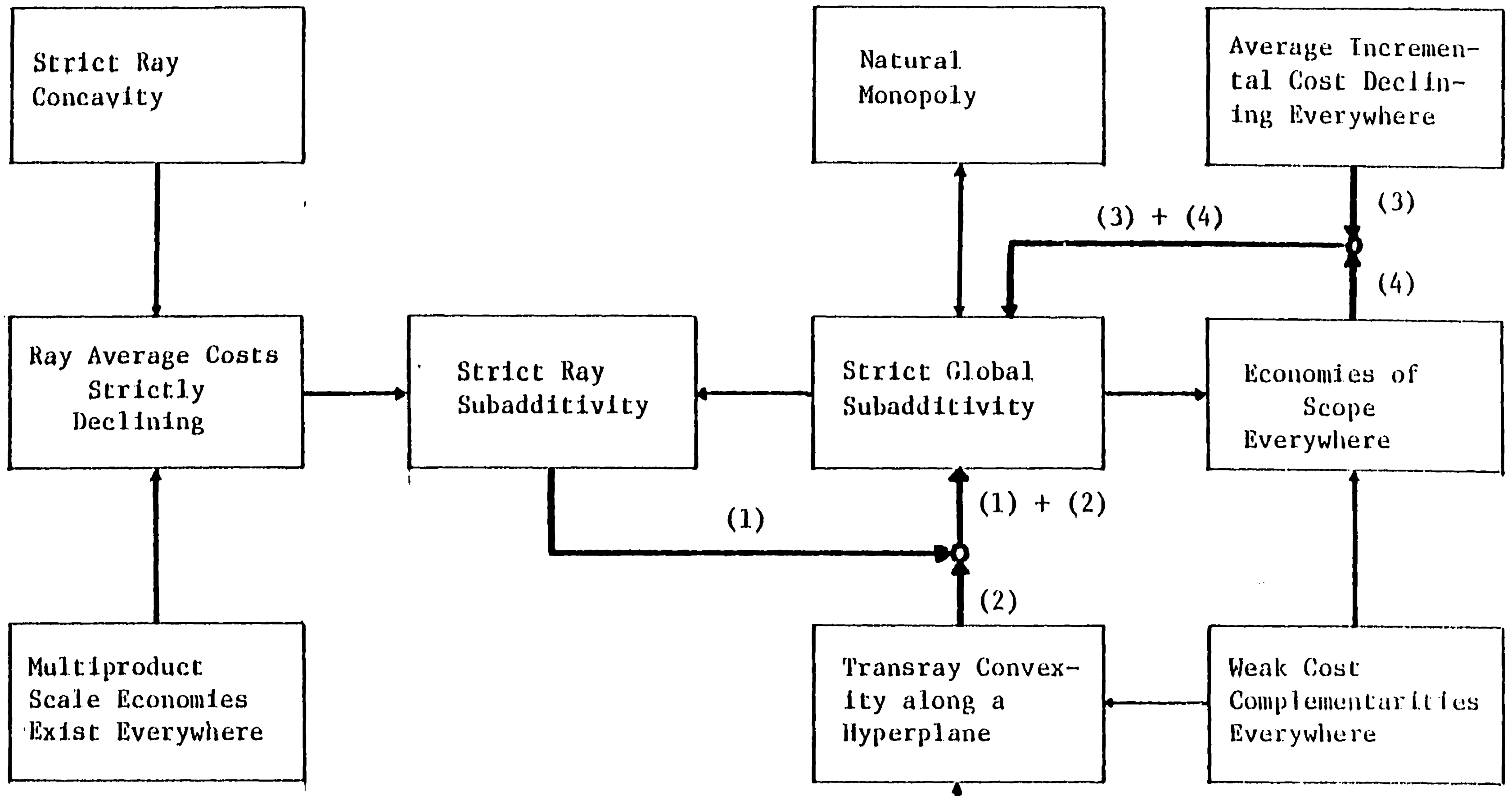

Figure 4.7 Summary of Multiproduct Cost Concept

Note that transray convexity, weak cost complementarity, and cost convexity are only sufficient conditions to guarantee transray cost advantages. A natural monopoly could still exist without transray convexity or weak cost complementarities.

Thus there are several tests that can be performed to indicate whether a cost function is globally subadditive. For example,

(1) Multiproduct scale economies are greater than unity and the cost function is convex everywhere;

(2) Multiproduct scale economies are greater than unity and weak cost complementarities hold everywhere;

(3) The cost function exhibits transray convexity along a hyperplane, and multiproduct scale economies are greater than unity up to that hyperplane;

(4) The cost function exhibits transray convexity and strict ray concavity; or

(5) Strict ray concavity and weak cost complementarities exist in the cost function.

Some of these tests are stronger than others. However, the basic idea is to guarantee the existence of ray subadditivity and transray convexity which are the sufficient conditions for natural monopoly (Figure 4.8). However, there is yet another set of tests which also provides sufficient conditions for subadditivity. As suggested by Baumol, Panzar and Willig (1979), decreasing average incremental costs through (or up to) output Y and economies of scope at Y also imply subadditivity at Y.

We will now turn to the issue of data requirements for these tests. Multiproduct scale economies can readily be derived from Eq. (4.6). The

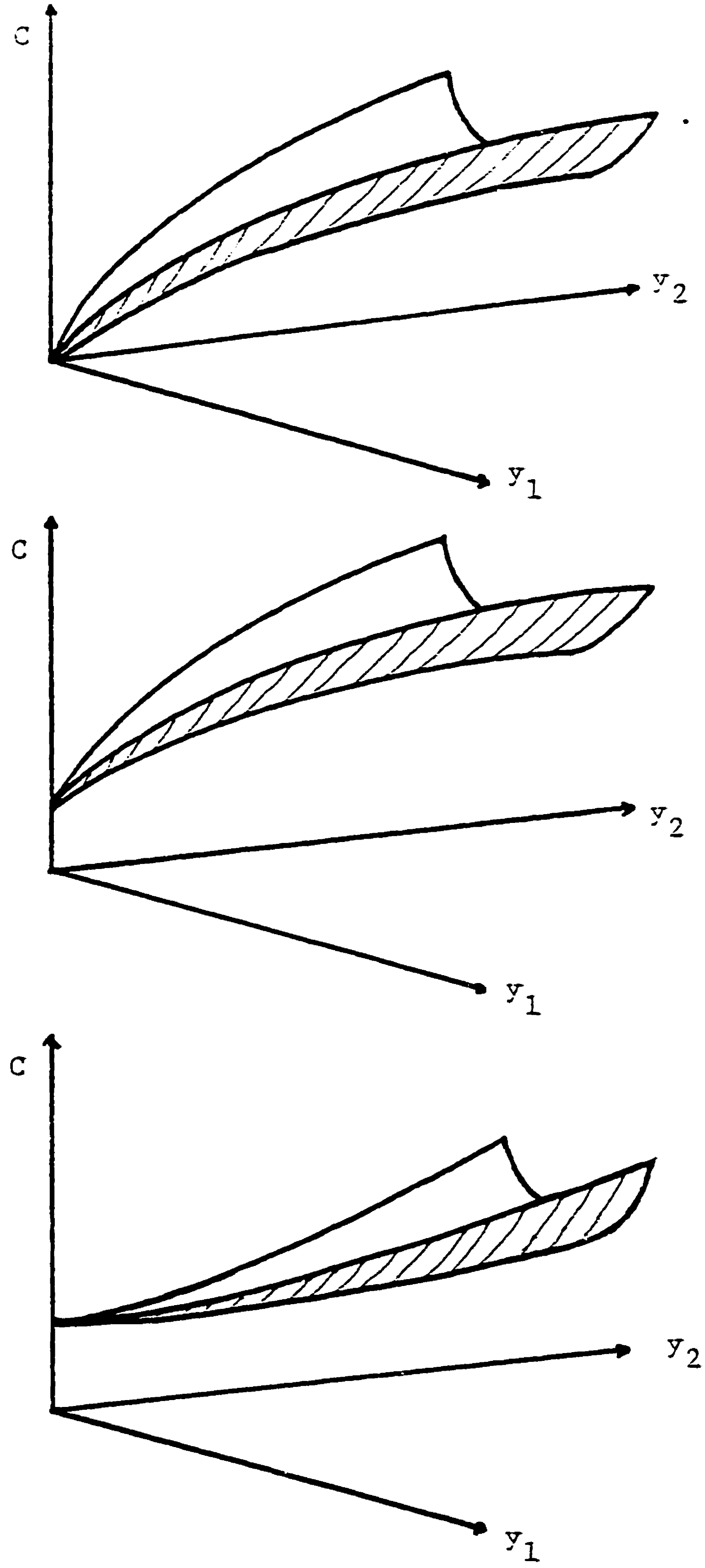

Figure 4.8 Ray Subadditivity and Transray Convexity as Sufficient Conditions for Natural Monopoly: Two-Product Case

second derivatives of the cost function with respect to output — the Hessian matrix, H — contain virtually all the information which is required to test for ray concavity, transray convexity, cost convexity, or weak cost complementarities. It is easy to test for the existence of ray concavity. A cost function is ray concave along a ray through Y = $(y_1,\ldots,y_n)$ if YHY' is negative. Recall that the conditions for weak cost complementarities at Y are simply

$$\frac{\partial C(\tilde{Y},W;t)}{\partial y_i\ \partial y_j} \equiv C_{ij}(\tilde{Y},W;t) < 0 \quad i \neq j\ ,\ \tilde{Y} \leq Y \qquad (4.15)\ \text{repeated}$$

$$Y > 0$$

Thus off-diagonal elements of a Hessian matrix provide the information for the test of weak cost complementarity between any two outputs.

It is also easy to see whether a cost function is convex everywhere by testing whether the Hessian matrix is positive-definte. The Hessian matrix H is positive-definite if all principal submatrices of the matrix H have positive determinants. A necessary condition for this is that all diagonal elements, $C_{ii} = \partial^2 C/\partial y_i^2$, $\forall i$, be positive. One can see that the test for cost convexity or weak cost complementarities between all output pairs could well be too severe in empirical studies involving many products.

However, a somewhat weaker test for subadditivity is to test for the existence of transray convexity directly. Transray convexity along a hyperplane is, in other words, cost convexity along a hyperplane. This is equivalent to the constrained mathematical optimization problem of minimizing total costs with respect to the output vector, subject to the constraints that these outputs are along a hyperplane:

$$\min_{Y} \; C(Y,W;t)$$

$$\text{s.t.} \quad \sum_i u_i y_i = v$$

$$u_i > 0, \; \forall i \tag{4.17}$$

where v is a scalar and u_i's are a vector of scalars.

Thus, the cost function is convex along a hyperplane if the bordered Hessian — given as follows — is positive-definite:[9]

$$H_B = \begin{bmatrix} H & u' \\ u & 0 \end{bmatrix} \tag{4.18}$$

where $u = (u_1, \ldots, u_n)$.

As indicated earlier, transray convexity only requires that the condition of Eq. (4.16) is satisfied for at least one hyperplane. This corresponds to saying that transray convexity is present if there is at least one vector u where the bordered Hessian H_B is positive—definite. One difficulty that immediately arises in this case is how to identify this vector in a systematic manner in empirical analysis. This has prevented the dire test of transray convexity from being very powerful in empirical studies where many outputs are involved.

From a practical point of view, then, the last set of tests listed above — decreasing average incremental costs plus economies of scope — although seemingly less analytically and computationally tractable — is nevertheless the most valuable method for testing for the existence of natural monopoly. It is computationally less attractive in the sense that the conditions for

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[9] Varian (1978), pp. 262-266.

decreasing average incremental costs and economies of scale should hold for every possible partition of the entire vector. Furthermore, there is no simple analytical way to test whether average incremental costs are strictly declining. Nevertheless, it does provide a useful computational vehicle to test for the existence of natural monopoly around the actual output vector. In the subsequent empirical analysis, this will prove to be a useful tool.

CHAPTER FIVE

FORMULATION OF A GENERAL MULTIPRODUCT COST FUNCTION FOR THE TRUCKING INDUSTRY

I. Measures of Trucking Output

A fundamental difficulty associated with studying trucking technology is finding an appropriate measure of trucking output. While it is clearly useful to describe trucking technology by a multiproduct cost function, it is less clear how trucking output should be specifically defined. This is also the case for transportation services other than trucking. Empirical studies of transportation technology have long recognized that because transportation output is highly heterogeneous, it is virtually impossible to understand the true nature of technology if quality differentials and the composition of output are not taken into account.[1/] In fact, traditional aggregate measures such as tons, ton-miles, or shipments have led to somewhat biased estimation results. For example, studies by Friedlaender-Spady-Wang Chiang (1981) and Wang Chiang (1979) have indicated that many of the estimated scale economies in the trucking industry—as suggested by earlier studies of motor carriers' costs—are mainly due to a failure to account for these quality dimensions. These conclusions of Frielaender and her associates were based upon an empirical analysis of trucking costs that used

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[1/] For example, Warner (1965), Griliches (1972), Koenker (1977), Gordon and de Neufville (1977), Spady and Friedlaender (1978), Harmatuck (1979), Braeutigam, Daughety and Turnquist (1980), Jara-Diaz (1981).

three different specifications: one simply used ton-miles as an output measures without any quality adjustments; the other two added a set of operating characteristics to reflect the heterogeneity of trucking output in two slightly different formulations — a "hedonic-output" formulation and a "technological-condition" formulation. Their estimation results for general-freight regional carriers indicated the presence of economeies of scale in the cost function that was estimated using ton-miles alone with no quality variables. However, these scale economies vanished as output was adjusted for operating characteristics.

Trucking output can be characterized by at least four distinct dimensions:

- Commodity moved
- Distance moved or origin/destination of the movement
- Quantity moved
- Level of service

The importance of commodity attributes in characterizing trucking output is that certain commodities may involve special equipment and/or handling requirements. For example, fresh fruit and vegetables need to be transported in refrigerated cars; and fragile goods require special care in handling and transporting. Shipment size is important due to the fact that smaller shipments require more handling and thus higher costs. Distance is an important dimensions since shipping over a long haul requires less terminal activity relative to the linehaul journey than shipping over a short haul. Finally, level-of-service attributes such as transit time and reliability are useful because providing a higher level of service requires more expenditure in equipment and/or labor. Level of service serves as the "quality" in traditional market analyses of quality competition.

The fundamental difference between using origin/desintation and using distance to characterize spatial aspects of trucking output is clear: the former is location-specific and the latter is not. Specifying given origin-destination points always implies distance, but the converse is not true. Thus both have the ability to reflect the effects of length of haul, the most critical variable to have been identified in empirical studies on trucking technology and costs. However, in terms of identifying the existence of cost complementarities between long-haul and short-haul trucking, using output variables characterized by origin/destination points has the advantage of being location-specific. Thus in the O-D case, these cost complementarities can be examined within a network on a corridor-by-corridor basis, while in the case where distance is used alone one must use an aggregate output measure.

The most disaggregate unit of measuring trucking output is the specific shipment rather than tons or ton-miles. An individual shipment with its commodity, distance or location, quantity, and level-of-service attributes is a distinct output. For example, one distinct unit of output is given by a shipment of twenty tons of fresh lettuce moving from Los Angeles to San Francisco (400 miles) by next-day delivery, TL service. Another example, is a shipment of 500 pounds of computer equipment using LTL service, moving from Boston to Seattle (3000 miles), seven to ten days delivery. Clearly each of these is quite a different output. Note that a shipment of 100 tons of a commodity from locations A to B is different from 100 one-ton shipments of the same commodity, moving along the same corridor in the same period. Although total tonnage and ton-miles are identical in both cases, the technologies of handling would be quite different.

Let us define the following notations:

SHIP : shipment
COMM : commodity
SIZE : shipment size
DIST : distance
O : origin point
D : destination point
LOS : level of service
TONS : tons
TON-MILES : ton-miles

Thus SHIP(COMM, SIZE, O, D, LOS) describes a trucking output at the most disaggregate level; and SHIP(COMM, SIZE, DIST, LOS) gives the same disaggregate measure but is not location-specific. Naturally, the total number of shipments will be an output measure at the most aggregate level since all four attributes are ignored. The traditional measures of tons or ton-miles lies in between these two extremes and represent the following aggregations:

$$\text{TONS} = \sum_{\text{COMM}} \sum_{\text{SIZE}} \sum_{\text{O}} \sum_{\text{D}} \sum_{\text{LOS}} \text{SIZE} \cdot \text{SHIP}(\text{COMM},\text{SIZE},\text{O},\text{D},\text{LOS})$$

$$\text{TONS} = \sum_{\text{COMM}} \sum_{\text{SIZE}} \sum_{\text{DIST}} \sum_{\text{LOS}} \text{SIZE} \cdot \text{SHIP}(\text{COMM},\text{SIZE},\text{DIST},\text{LOS}) \qquad (5.1)$$

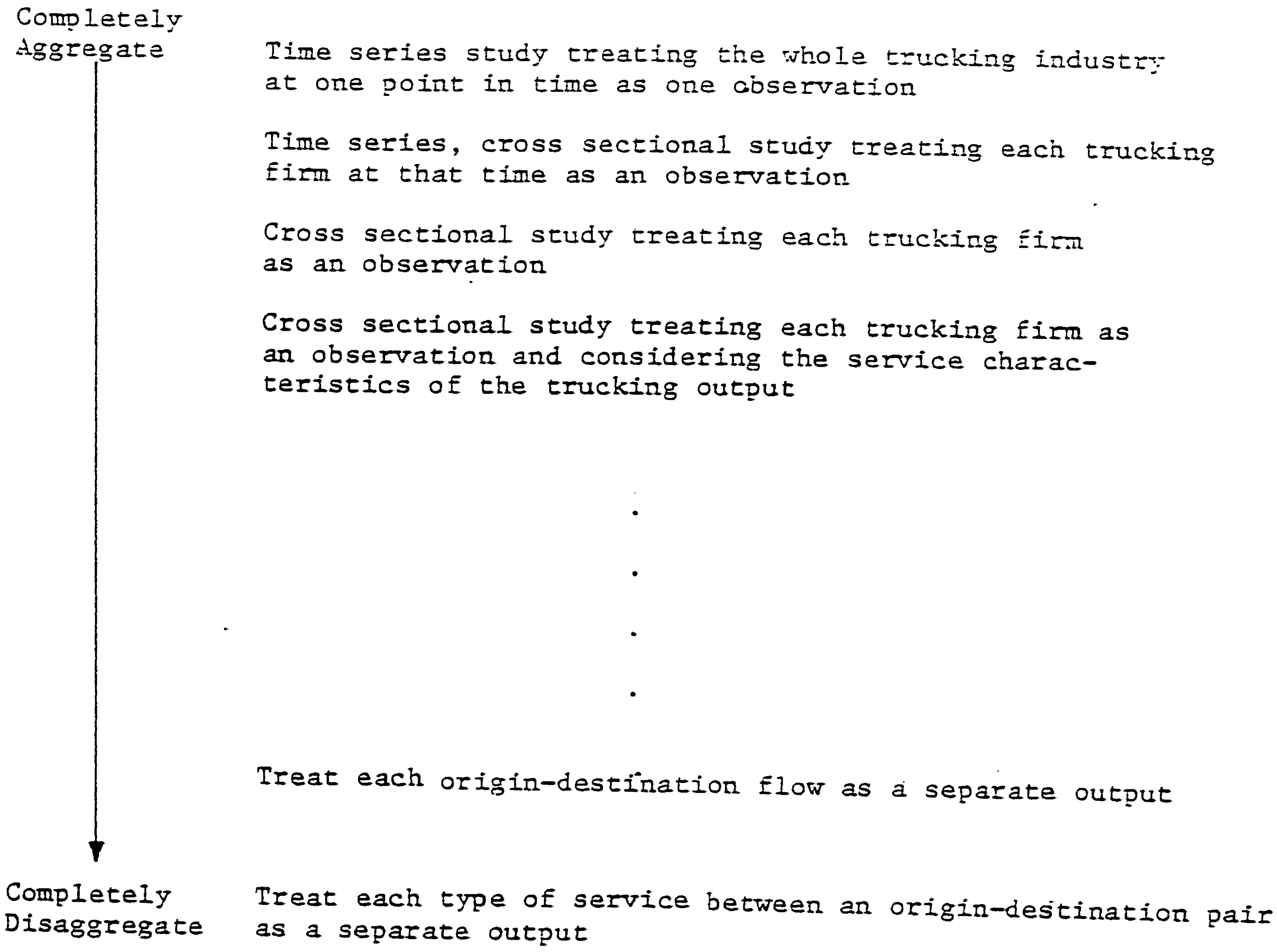
$$\text{TON-MILES} = \sum_{\text{COMM}} \sum_{\text{SIZE}} \sum_{\text{O}} \sum_{\text{D}} \sum_{\text{LOS}} \text{SIZE} \cdot \text{DIST} \cdot \text{SHIP(COMM,SIZE,O,D,LOS)}$$

$$\text{TON-MILES} = \sum_{\text{COMM}} \sum_{\text{SIZE}} \sum_{\text{DIST}} \sum_{\text{LOS}} \text{SIZE} \cdot \text{DIST} \cdot \text{SHIP(COMM,SIZE, DIST,LOS)}$$

This suggests that ton-miles is a better aggregate measure than tons since less informaiton is lost through aggregation. And, for the same reason, both tons and ton-miles are better aggregate measures than number of shipments.

As discussed earlier, it is desirable to describe trucking output as being multiproduct in order to study the nature of economies in the trucking industry. Trucking operations involve the joint production of these multiple products through a physical network and a routing of vehicles over the network. However, the treatment of these multiple products will differ with the level of aggregation as will the approach used to model trucking costs and technology. At the completely aggregate level, it is possible to utilize a time-series analysis that treats the whole trucking industry at one point in time as a single observation. At the completely disaggregate level, it is possible to treat each type of service (commodity type, shipment size, level of service) in each origin-destination corridor as a separate output. The whole spectrum of possibilities is shown in Figure 5.1.

From a theoretical viewpoint, modeling trucking output at a low level of aggregation permits greater understanding of the nature of network operations. For example, it would be very attractive if one could treat each type of trucking service in each origin-destination corridor as an output since this would provide an opportunity to distinguish the existence of economies of large output, of network configraution, and



Completely Aggregate

Time series study treating the whole trucking industry at one point in time as one observation

Time series, cross sectional study treating each trucking firm at that time as an observation

Cross sectional study treating each trucking firm as an observation

Cross sectional study treating each trucking firm as an observation and considering the service characteristics of the trucking output

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Treat each origin-destination flow as a separate output

Completely Disaggregate

Treat each type of service between an origin-destination pair as a separate output

Figure 5.1 Alternative Approaches to Treating Trucking Output of network operations. Unfortunately, it is virtually impossible to implement this level of disaggregation in empirical analysis.

The maximum possible number of one-way links in a network of n nodes is n(n-1)/2. A typical common carrier of general freight operates over a complicated network of many links and nodes, with a network of more than 600 origin-destination pairs being quite common. Indeed, large carriers such as Roadway operate over more than 8000 O-D pairs.[2/] It is therefore impossible to model trucking output at the individual corridor level in the real world without extensive aggregation. This problem becomes even more serious when a cross sectional analysis of carriers is utilized, since each carrier typically operates over a different, O-D-specific network.

Thus the real issue in defining multiple outputs for modeling trucking technology is not how to arrive at a theoretical concept of stratification; rather, it is what feasible level of aggregation will yield the maximum knowledge of the underlying technology through empirical analysis. The first requirements for such analysis are computational feasibility and data availability.

In terms of data availability, the Continuous Traffic Survey (CTS) made in 1976 provides a vast amount of information concerning the movements of a large number of carriers. Thus it would in principle be possible to define outputs in terms of specific corridors. Since,

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[2/] In terms of Standard Metropolitan Statistical Areas (SMSA's) and Standard Point Location Codes (SPLC's).

however, costs should not be particularly corridor-specific, given the overall network configuration,[3] this suggests that a reasonable approach to aggregation would be to utilize overall measures of network configuration in conjunction with generic measures of output over a corridor. Thus there seems to be little reason to define output in terms of specific O-D pairs, as long as the overall network configuration and utilization are incorporated into the analysis.

Even if output is measured in terms of generic corridors there is still considerable scope for disaggregation. Since, however, the number of estimated parameters rises dramtically with the number of ouptuts utilized in the cost function, this suggests that output be defined in fairly aggregate terms. In this respect the following stratification appears to be both computationally tractable, while capturing the essence of the differences in various types of trucking movements.

- LTL traffic with length of haul under 250 miles
- LTL traffic with length of haul of 250 - 500 miles
- LTL traffic with length of haul over 500 miles
- TL traffic

Two factors enter into this stratification: length of haul and type of service — TL or LTL. These two attributes capture most of the characteristics in trucking output that have significant impacts upon technology and thus upon costs. The technology of moving TL traffic is very different from that of moving LTL traffic. Compared to LTL

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[3] Thus, if two firms had identical network configurations, their costs of shipping between any two O-D pairs of comparable distance should be equal. Consequently, if everything else is held equal, the costs of shipping between Boston and Washington, D.C. should be comparable to the costs of shipping between San Francisco and Los Angeles.

service, TL service typically involves larger shipment sizes, larger vehicle loads, and faster service times, since it requires no terminal consolidation. Furthermore, commodities handled by TL service are also typically different from commodities handled by LTL service. TL shipments usually consist of freight classified by the ICC as specialized — e.g., heavy machinery or liquid petroleum products — which typically require special equipment and handling, while LTL shipments usually consist of general freight. Moreover, the classification of TL/LTL captures the inherent differences in transit time and reliability between these two types of services.[4/] Thus this stratification reflects most of the useful commodity, quantity, and level-of-service attributes that characterize trucking output. More detailed variation by commodity (apples or oranges) and by quantity (500 or 800 pounds) is less meaningful and can be ignored.

The stratification of LTL traffic into three categories based on length of haul — less than 250 miles, between 250 and 500 miles, over 500 miles — is based on technological considerations. LTL shipments must be consolidated into large lots at terminals for intercity movements. However, the objectives and procedures of terminal operations for short-haul and long-haul traffic are in fact very different from each other. Since LTL shipments involve extensive handling, labor costs typically

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[4/] While there are clearly other dimensions to level of service than truckload and LTL traffic, they are probably endogenously determined. Thus to include them in the cost function would require the simultaneous formulation of both supply and demand equations. Fortunately, service time on linehaul variations among common carriers of general freight do not appear to be very great.

represent a high percentage of total costs. Statistics show that approximately 45 percent of LTL freight revenue is spent in pickup, delivery and terminal operations. This percentage increases dramatically as the length of haul rises. For short-haul operations, carriers attempt to utilize direct service for competitive reasons, typically using the standard of next-day delivery. Thus for short-haul movements, shipments are usually dispatched to adjacent terminals for consolidation with other shipments bound for the same destinations and linehaul vehicles are often dispatched without being fully loaded. By contrast, the objective of long-haul LTL operations is to utilize fully the advantages of routing strategy and terminal operations to minimize overall shipping costs. Direct service and speed are, in general, not of principal concern. Freight may be consolidated more than once, at local as well as breakbulk terminals, and trailers are expected to be fully loaded. Thus the terminal and handling costs associated with long-haul traffic are proportionately higher than those associated with short-haul traffic.

There is no clear line to divide a market between the short haul and the long haul. However, 250 miles could well be the limit of direct-service LTL operations. Similarly, lengths of haul over 500 miles are typically too far to allow direct serivce. By contrast, 500 miles could well be the minimum distance for breakbulk terminal consolidation. Thus it seems reasonable to regard shipments under 250 miles as short-haul movements, with those whose length of haul lies between 250 and 500 miles as being intermediate movements.

This stratification also has important policy implications since one of the important policies issues is to what extent cost complementarities exist between short-haul and long-haul markets. In a deregulated environment, would long-haul carriers encroach upon the short-haul and intermediate-haul markets because of lower costs? Or alternatively, do short-haul carriers have the ability to expand their services into intermediate- or long-haul markets? Would intermediate-haul or short-haul carriers remain in operation in the absence of regulation? The stratification of output based upon length of haul provides a good opportunity to investigate these questions.

II. Global Measures of Trucking Network

Since location-specific output definitions are not feasible to use in most empirical applications, it is useful to introduce global network measures in the cost function to reflect the role of network effects upon costs. In this regard, two aspects of trucking network are particularly important: network configuration and network utilization. Network configuration basically reflects the operating rights granted by the ICC over which a carrier operates. A large network with many terminals and routes has higher potential to: 1) provide direct service between any points of origin and destination; and 2) perform terminal consolidations to achieve economies of traffic density. Thus network configuration can be measured from at least two points of view: the degree to which the network is fully connected and the size of the coverage of the network.

Network connectivity has been studied extensively in graph theory, and various measurable indices have been suggested.5/ For our purposes,

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5/ See Kansky (1963), Garrison and Marble (1965), Gordon and de Neufville (1977).

a useful measure is the traditional Gamma index. For a given network of n nodes, the Gamma index gives the ratio of total number of connected links over the possible maximum number of links:

$$\gamma = \frac{\ell}{n(n-1)/2} \qquad (5.2)$$

where: γ = Gamma index, $0 \leq \gamma \leq 1$

ℓ = number of connected links

n = number of nodes

$n(n-1)/2$ = the possible maximum number of links.

Thus a value of Gamma index close to one indicates that the network is highly connected.[6] A highly connected network would enable a firm to utilize its equipment more efficiently.

There are many ways to describe the size of a network, e.g., number of terminals, number of routes, number of route-miles, number of areas served by the network, number of cities serviced by the network, etc. However, these variables only measure the physical size of the network and do not reflect the effects that a large network may have on network operation. A better measure, known as the indirect routing index (IDRI) is thus suggested. The IDRI for a network is defined as

$$\text{IDRI} = \frac{\Sigma\ \text{tons}_{ij} \cdot \text{dist}^1_{ij}}{\Sigma\ \text{tons}_{ij} \cdot \text{dist}^0_{ij}} \qquad (5.3)$$

where: tons_{ij} = tons moving from point i to point j

dist^0_{ij} = direct distance bewteen i and j

dist^1_{ij} = routing distance from i to j

Thus a low value of IDRI suggests a large network with many routes and terminals such that direct routing becomes efficient.

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[6] Other connectivity measures such as the Alpha index are defined in ways that are quite similar to the Gamma index and do not seem to provide much additional information while providing greater computational complexity.

Network operation is conditional on network configuration. Given a network configuration, operating strategies are performed to route vehicles through the network to minimize costs and maximize profits. Thus a global description of both network operation and network configuration is network density which measures network connectivity as well as the flows over the specific links (see Figure 5.2). A possible measure of network density is the recently developed Chi index, which can be expressed as follows:[7]

$$\chi = (\Sigma\sqrt{f_j})^2/(\Sigma f_j)n(n-1) \tag{5.4}$$

where: χ = Chi index, $0 \leq \chi \leq 1$

f_j = flow in link j, defined as tons, ton-miles, or vehicle-miles

n = number of nodes

$n(n-1)$ = the possible maximum number of two-way links.

The term $(\Sigma\sqrt{f_j})^2/(\Sigma f_j)$ will reach its maximum value and equal the number of links when flows are equally distributed, i.e., $f_1 = f_2 = ,\ldots, = f_n$. Thus a higher value of Chi implies a network where the system spreads the traffic relatively evenly over the whole network; a lower value of Chi implies a network where the system concentrates flows on a relatively few links. A network with low Chi index indicates the tendency that more traffic consolidation has been performed.

An additional global measure of network characteristics is terminal density. This variable can be defined in one of two wyas: total number of terminals divided by total number of route-miles of the network; or total number of terminals divided by total number of ton-miles of traffic

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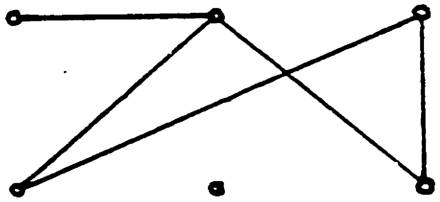
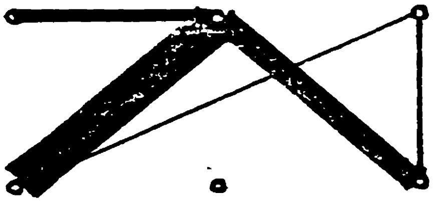
[7] See Gordon (1974) Gordon and de Neufville (19 7) for a fuller description of the Chi index.

1. Network Connectivity



2. Flow Density



3. Networks with Same Connectivity but Different Densities

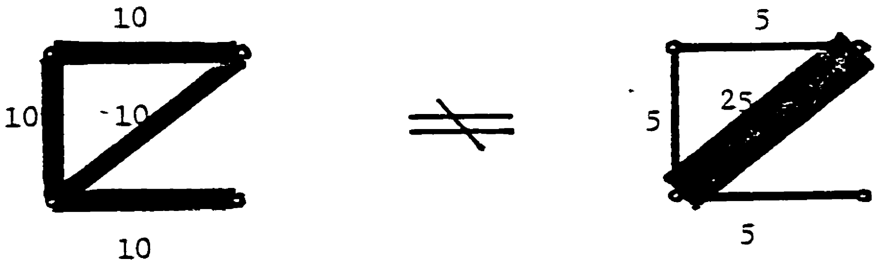


Figure 5.2 Measures of Network Density

handled by the network. The effects of terminal density on trucking costs are positive as well as negative. Terminals per route-mile measures the density of terminals in a network. A high density terminals per route-mile may indicate a large number of terminal consolidations and thus possible lower pickup and delivery costs. On the other hand, more terminals per route-mile could also indicate a poor network configuration and high terminal costs. More terminals per route-mile could also suggest an attempt to provide higher pickup and delivery services. Similar arguments also apply to the variable terminals/ton-mile. Thus the net effect of terminal density upon costs in an empirical analysis will depend on which force is dominant. Although this ambiguity could disappear if breakbulk terminals were incorporated into the definition of terminal density, data on breakbulk terminals are not available.[8/]

III. A Multiproduct Joint Cost Function for the Trucking Industry

Since the utilization of a network implies that outputs are produced jointly by one firm over the network, it is necessary to specify a multiproduct joint cost function to analyze trucking technology. As a first approximation, the following cost formulation is reasonable:

$$C = C(Y,W;T(N,Q)) \tag{5.5}$$

where: C = total cost of a carrier

$Y = (y_1,\ldots,y_n)$ = a vector of outputs of a carrier as defined earlier in this chapter, measured in ton-miles

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[8/] An effort was made to obtain this information directly from the carriers. However, they were typically either unwilling or unable to provide information on the nature of their terminal operations.

$W = (w_1,\ldots,w_m)$ = a vector of factor prices

T = a vector of technological conditions in production of a carrier which includes global measures of network characteristics and operating characteristics

$N = (N_1,\ldots,N_k)$ = a vector of aggregate network characteristics of a carrier

$Q = (Q_1,\ldots,Q_\ell)$ = a vector of aggregate operating characteristics of a carrier.

Both N and Q are defined as the underlying technological conditions in production. Aggregate operating characteristics include variables such as insurance costs per ton-mile, labor costs per shipment and vehicle-miles per vehicle, etc. Insurance costs reflect differences in fragility and costs of special handling. The inclusion of insurance as an operating characteristic should serve to caputre the differences in the composition of outputs and the requirements of special transport and handling, equipment and labor. Labor costs per shipment reflects the requirements of labor in pickup/delivery and handling, while vehicle-miles per vehicle gives the average mileage traveled per vehicle — a measure of equipment utilization. Note that transport/handling equipment and its utilization, pickup/delivery systems, and terminal operations are the fundamental technologies in trucking operations.

Moreover, since there are still product differentials in our output definitions, we adjust these differentials hedonically by product-specific network and operation characteristics. This leads to our general multi-product joint cost function:

$$C = C(\Psi, W; T(N,Q)) \tag{5.7}$$

$$\psi_i = \psi_i(y_i, D_i, t_i) \quad , \quad i = 1,\ldots,n \tag{5.7a}$$

where: $\Psi = (\psi_1,\ldots,\psi_n)$ = a vector of effective trucking outputs

$\psi_i(\cdot)$ = hedonic output function for y_i

$D_i = (d_{i1},\ldots,d_{ik})$ = a vector of product-specific network characteristics

$t_i = (t_{i1},\ldots,t_{i\ell})$ = a vector of product-specific operating characteristics

Product-specific hedonic variables could include variables such as average length of haul and variations, average load per vehicle and variations, average shipment size and variations, and variables of measuring commodity-mix in each output aggregation, etc.

By conventional aggregation theory, the hedonic function, $\psi_i = \psi_i(y_i,D_i,t_i)$, should be homogeneous of degree one in y_i. In other words, doubling the level of y_i will double the level of effective output ψ_i. A natural functional form for Eq. (5.7a) would then be

$$\psi_i = y_i \cdot \phi_i(D_i,t_i) \tag{5.7b}$$

Therefore, as indicated by Baumol, Panzar and Willig (1979), the hedonically adjusted effective output can be interpreted as an aggregate output along a ray in the output space defined by the function ϕ_i. Thus, in theory, if enough hedonic variables were included, the multiproduct cost function with hedonic adjustments would in fact be identical to a multiproduct cost function at the completely disaggregate level.

The cost function (Eq. (5.7)), and the hedonic output functions

Eq. (5.7b)) should be estimated simultaneously with the factor demand equations implied by Shephard's lemma to obtain efficient estimates. Factor demand equations associated with the general joint cost function can be written as

$$x_i = \frac{\partial C(\Psi, W; T(N,Q))}{\partial w_i} \quad i = i,m \qquad (5.8)$$

Under current ICC regulations, output level, operating characteristics, and network characteristics can all be assumed to be exogenous and beyond the control of the firm, at least in the short run. However, one can argue that some of these vaiables could still be endogenous, e.g., load per vehicle, since a general-freight carrier has the ability to manipulate load size by dispatching LTL freight to achieve overall benefits. However, average load per vehicle is still very much influenced by market demands which are determined in turn by operating rights and the rate structure. Thus it seems reasonable to treat all of the variables in the cost function as exogenous and independent of costs.[9]

Empirical estimation of a cost function requires an explicit functional form. Extensive research has recently been directed toward deriving flexible functional forms which place no a priori restrictions on elasticities of the underlying technology. Flexible functional forms have been proposed, including the generalized Leontief function (Diewert (1971)), the generalized Leontief joint cost function (Hall (1973)), the generalized square root quadratic function (Diewert (1973)), the translog function (Christensen, Jorgenson and Lau (1973)), the genera-

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[9] Even if a variable is found to be endogenous, statistical methods such as instrumental variables can usually be used in estimation to obtain consistent results.

lized translog function (Caves, Christensen and Trethaway (1978)), and the generlized Box-Cox function (Berndt and Khaled (1979)), among others.[10]

Generally speaking, flexible functional forms are second-order (or higher) approximations to a given cost or production function at certain points of expansion.[11] Being an arbitrary approximation, the functional form is free from many (but not all) possible restrictions on the technology being modeled, including cost elasticities, elasticities of substitution among factors and elasticities of transformation among outputs, etc. Common restrictions implied in conventional cost or production functions such as the Cobb-Douglas or CES include input-output separability, constant cost elasticities and constant elasticities of substitution. Although a flexible cost or production function will generally not be self-dual, i.e., one cannot directly derive the corresponding production function from an estimated cost function, and vice versa (Burgess (1975)), this is not a serious problem since duality theory ensures that both production functions and cost functions can provide an equal level of information concerning the underlying technology.

The most commonly used flexible function in empirical work is the translog function. A nice property of the translog cost function is that it permits a wide range of tests of various hypotheses concerning the structure of technology to be easily performed using the estimated parameters. Moreover,

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[10] In fact, the last two functional forms are equivalent.

[11] Usually at sample means.

it also permits the simple imposition of parameter restrictions in estimation to ensure that the cost function is well-behaved. For example, cost minimization requires that the cost function is homogeneous of degree one in factor prices—a condition that can be easily imposed in a translog cost function, but not in some of the other flexible functions.[12]

In spite of its advantages for empirical estimation, the translog function suffers from the defect of being undefined for zero values of the variables.[13] However, this problem is not overwhelming since it is possible to incorporate zero values of the variables by using various transformations of the translog function.[14] A more fundamental problem in terms of economic intuition is that the translog cost function implies that the joint cost of producing the whole output vector would be zero if any one of the output vectors has zero output, since $C(Y,W;T(N,Q)) = 0$ for a translog cost function. However, this is more of a problem in prediction than in estimation since zero output variables are far from the sample mean, and all estimated flexible functions are technically valid only at the point of approximation. Nevertheless, this does not prevent one from inferring the underlying technology at the local region around the sample means. Furthermore, the problem of whether local properties hold globally is the same among all flexible

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[12] For example, it is difficult to impose the condition of homogeneity of degree one in factor prices in a quadratic cost function.

[13] This shortcoming precluded defining output in terms of corridors whose length was greater than 500 miles since many firms in the sample did not operate on corridors this long. At the moment, we are exploring the possibility of defining output in terms of corridors whose length exceeds 500 miles.

[14] See, for example, Berndt and Khaled (1979).

cost functions.[15] As the levels of output move far from their mean values, inferences about the global behavior of costs become less reliable. Thus this is a common weakness of all flexible cost functions in testing hypotheses that require global information, e.g., subadditivity. Nevertheless, the translog cost function presents more of a problem in this respect since, for example, incremental costs cannot be calculated without assuming a fixed cost.[16]

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[15] Caves and Christensen (1978) performed a study to address this issue.

[16] We will return to this issue in Chapter Six.

CHAPTER SIX

AN EMPIRICAL ANALYSIS: A MULTIPRODUCT JOINT COST FUNCTION FOR GENERAL COMMODITY CARRIERS

I. Data and Variables

A. Data

Published data that permit analysis of trucking costs using disaggregate output variables are almost nonexistent. Thus most studies have utilized ton-miles as a single output measure and relied on data from Trinc's Blue Book of the Trucking Industry which provides annual information on revenues, expenditures, vehicle ownership, and revenue ton-miles, etc., for each regulated common carrier. Although this has been the data source for the majority of empirical studies on trucking costs, its output data are aggregated into ton-miles, and important data items are sometimes missing. This has even created difficulties in estimating an aggregate cost function with hedonic output adjustments.[1/]

Data in Trinc's Blue Book are in fact assembled from the ICC Annual Reports for Class I and II Motor Carriers, which essentially give the same information as Trinc's Blue Book, but at a more disaggregate level. However, data are still not available by corridor or by market from the ICC Annual Reports. To find information on traffic flows by corridor or O-D pairs, one must go to the Continuing Traffic Survey,

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[1/] See, for example, Spady (1978) for a discussion of the assumptions and procedures used in estimating useful data from Trinc's Blue Book.

which is collected by the various rate bureaus and has recently been made available to the ICC. This is a waybill survey, which samples the traffic of the relevant carriers. The information for these samples are assembled into tapes, which we will refer to as the Continuing Traffic Survey Tapes (CTS tapes), that give quite detailed information on each individual shipment such as origin point, destination point, shipment size, kind of shipment (LTL, TL, minimum charge), regular and special revenues, type of handling, etc. These data provide sufficient information on the nature of shipments permit the estimation of a multiproduct cost function for the trucking industry. Unfortunately, since these tapes are proprietary, they are not generally available to the public. However, the ICC made them available for this research, with the stipulation that no firm-specific data or information be divulged.

This analysis consequently uses the highly disaggregate data in the CTS tapes to derive measures of four output types, which are stratified by length of haul and type of service — TL or LTL. Aggregate measures of product-specific operating characteristics as well as global network characteristics were also derived from these data using fairly complicated procedures which will be discussed below.

Other data sources for this study include the ICC Annual Report tapes which give information such as labor costs and capital costs for each subcategory, as well as National Highway Carriers Directory, which provides the data on carriers' routes and terminals. The fuel price informaiton was taken from Plott's Oil Price Handbook, which has data on fuel prices for 55 representative cities in the United States.

Since the CTS data were available for 1976 for a limited number of carriers, we developed a data base for 105 general-freight carriers in 1976, in which 90 carriers are interregional/transcontinental carriers with annual revenues of more than 100 million ton-miles (see Appendix A).

B. Variables

1. Factor Prices and Shares

We classify input factors into five categories, namely labor, fuel, revenue equipment capital, purchased transportation, and "other," which represents a residual variable representing materials and nonspecific capital. Data for deriving these factor prices and factor shares were taken from the ICC Annual Report tape (1976).

The simplest approach to derive a labor price is to divide total labor expenditures by total number of employees. This does not give a good measure of labor costs, however, since labor is not a homogeneous entity: different types of labor receive different levels of compensation. To avoid this aggregation problem, we utilized a divisia index. Three types of labor expenditures (including benefits) were considered: 1) supervisory and salaried clerical; 2) linehaul, pickup/delivery and terminal platform operations, as well as repair services; and 3) other, to arrive at an aggregate measure of labor price through:

$$w_1 = \sum_{i=1}^{3} S_{1i} w_{1i} = \sum_{i=1}^{3} \left[\frac{EXP_{1i}}{\sum_{j=1}^{3} EXP_{1j}} \cdot \frac{EXP_{1i}}{x_{1i}} \right] \qquad (6.1)$$

where: w_1 = labor price index

w_{1i} = price of labor, type i

x_{1i} = number of employees of type i

S_{1i} = labor expenditure share for type i labor

EXP_{1i} = labor expenditures of type i

Table 6.1 shows the share of each type of labor and the average labor price index by size of carrier. Carrier size was determined by the level of annual revenue ton-mile. It is interesting to note that larger firms have lower percentage of labor expenditures on line-haul, pickup/delivery and terminal platform, but higher percentages in the other two categories.

The Annual Report tapes give the total expenditures on fuel and fuel taxes. The price of fuel (w_2) was taken from Plott's Oil Price Handbook (1977), which contains the average retail prices of regular grade gasoline (including taxes) at service stations in 55 representative cities. These citywide fuel prices were aggregated to derive regional fuel prices which were then applied to each carrier according to the region in which it is located.

Revenue equipment capital costs are "capital costs minus depreciation" for 1) trucks, 2) tractors, 3) semi-trailers, 4) full trailers, and 5) other equipment. We also used the divisia index approach to develop an equipment capital price index for these revenue equipment categories. Since the data in the Annual Report tapes do not contain information to estimate depreciation costs by equipment type, we estimated an average depreciation rate as "accumulated depreciation for carriers' operating property revenue equipment" divided by "carriers' operating

Table 6.1 Labor Shares and Average Labor Price Index by Size of Carrier (%)

	Carrier Size (millions of ton-miles/year)		
	Less than 100	Between 100 - 500	Over 500
Labor Share			
Supervisory and salaried clerical	26.5	28.3	29.8
Linehaul, pickup/delivery and terminal platform	72.3	69.6	66.8
Other	1.2	2.1	3.4
Total	100.0	100.0	100.0
Average Labor Price Index ($/employee)	16,979	17,571	16,870

Source: ICC, Annual Report tape, 1976.

property revenue equipment" and applied this rate to each equipment type. Carriers' net equipment expenditures reported in the Annual Report tape were added to a 14-percent opportunity cost to arrive at total equipment capital costs.[2/]

The Equipment Capital Price index was then derived as

$$w_3 = \sum_{i=1}^{5} S_{3i} w_{3i} = \sum_{i=1}^{5} \left(\frac{EXP_{3i}}{\sum_{j=1}^{5} EXP_{3j}} \cdot \frac{(1-r)EXP_{3i}}{x_{3i}} \right) \qquad (6.2)$$

where: w_3 = Equipment capital price index

w_{3i} = Equipment capital price, type i

x_{3i} = amount of equipment, type i

S_{3i} = equipment expenditures share for equipment type i

EXP_{3i} = equipment expenditures of type i including 14% opportunity cost

r = depreciation rate on capital equipment

"Purchased transportation" costs are those expenditures on 1) rented transportation equipment, and 2) purchased transportation services. The price of purchased transportation was also derived using a divisia index. First, we estimated a price index for rented transportation (trucks) with drivers and without drivers. Next, a price index was estimated for purchased transportation services by motor carriers, railroads, water carriers, or other. These two prices were then weighted

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[2/] 12 percent for 1972 as suggested by Spady and Friedlaender (1978), plus 2 percent for inflationary increases in interest rates from 1972 to 1976.

to arrive at the final price index for purchased transportation, w_5.

"Other" factor costs include capital costs excluding revenue equipment, as well as other costs not elsewhere classified. In other words, they represent the residual of the total operating costs (including opportunity costs on capital) minus costs of labor, equipment (including opportunity costs), fuel, and purchased transportation. The price of the "other" factor (w_4) was thus derived by dividing this residual category by "carriers' operating property net, excluding revenue equipment owned" which was taken as a measure of the physical quantity of these costs.[3/]

Table 6.2 summarizes the factor shares by size of carrier. Generally speaking, the shares of factor expenditures are relatively uniform among firm sizes. However, there are some interesting differences. For instance, the percentage of purchased transportation is higher for carriers with annual ton-miles between 100 and 500 million, and lower for the smaller and larger carriers. A reasonable interpretation of this would be that the larger carriers usually have more transport equipment moving over more extensive networks and are therefore better able to adjust their own vehicle supplies with fluctuating demand, while smaller carriers in general would have less incentive to purchase or rent transportation facilities. Thus intermediate-sized firms require more hired transportation to meet their demands.

[3/] Carrier operating property net excluding revenue equipment owned = (carrier operating property excluding revenue equipment owned) - (reserve for depreciation and amortization excluding revenue equipment owned).

Table 6.2 Factor Shares by Size of Carrier (%)

	Carrier Size (millions of ton-miles/year)		
	Less than 100	Between 100 - 500	Over 500
Labor	62.9	62.4	62.8
Fuel	5.7	6.2	7.5
Revenue Equipment Capital	1.9	1.9	2.1
Other	22.7	22.0	22.1
Purchased Transportation	6.8	7.5	5.5
Total	100.0	100.0	100.0

Source: ICC, Annual Report tape, 1976.

Another interesting observation from Table 6.2 is that large carriers have a higher percentage of expenditure for fuel and equipment capital — an indication that these carriers are more capital-intensive. Although the labor share is not particularly low for large carriers, one should remember that, as indicated in Table 6.2, large carriers have less labor expenditures on "technical" employees than on "marketing" employees.

2. Outputs and Hedonic Variables

The ICC Continuing Traffic Survey tape provided the raw material for estimating the trucking outputs used in this analysis. A waybill in the CTS tapes give the shipment size, mileage, and associated expansion factor for each shipment. By simple aggregation, we can derive the aggregate ton-miles for each type of output defined in Chapter Five for each carrier, namely:

y_1 = LTL ton-miles with length of haul less than 250 miles
y_2 = LTL ton-miles with length of haul from 250 to 500 miles
y_3 = LTL ton-miles with length of haul greater than 500 miles
y_4 = TL ton-miles

Table 6.3 indicates that the large firms in our sample primarily serve the long-haul market while small firms serve the short-haul market.

Hedonic variables for adjusting ton-miles were also developed using the CTS waybill data. We have derived the following variables for each type of output in our data base:

- standard deviation of ton-miles
- average length of haul in miles
- standard deviation of length of haul
- average shipment size
- standard deviation of shipment size
- number of origin-destination pairs

3. Aggregate Network Measures

Since the CTS tapes give the flow of shipments rather than the flow of vehicles, they provide information on a "demand" network

Table 6.3 Distribution of Ton-Miles among Type of Output by Size of Carrier (%)

Output	Carrier Size (millions of ton-miles/year) Less than 100	Between 100 - 500	Over 500
y_1	19.3	7.1	0.7
y_2	19.9	14.8	3.9
y_3	9.2	14.3	41.9
y_4	51.6	63.8	53.5
Total	100.0	100.0	100.0

Source: ICC, Continuing Traffic Survey tape, 1976.

rather than a "supply" network. The origin and destination points of a shipment were described in terms of standard point location codes (SPLC) in the waybills. A standard "point" in location is typically smaller than a city, but does not necessarily represent a terminal. Shipments originating from or arriving at adjacent SPLC's may well utilize the same terminal. A careful examination of route/terminal maps and origin-destination points for some carriers suggests that it would be approxpriate to assume that shipments with origin (destination) points within a certain SMSA share the same terminal. We thus aggregated shipment flows between SPLC's into flows between SMSA's using the ICC SPLC/SMSA converter file to derive aggregate network measures.[4]

We calculated the conventional "1-γ" index, denoted by N_1, and "1-χ" index, denoted by N_2, for each carrier in our sample (where "γ" and "χ" represent the Gamma and Chi network indices respectively as defined in Eqs. (5.2) and (5.4). We derived the indirect routing index, referred to as N_3, as outlined in Eq. (5.3). The direct routing distance was assumed to be the air distance between origin and destination SMSA's or SPLC's which was estimated as a great circle distance taking latitudes and longitudes of two points as inputs (see Wang Chiang (1978)).

The network maps contained in the National Highway Carriers Directory do not indicate whether a terminal is used for local service, consolidation, or breakbulk. Although a mail survey was conducted among

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[4] SPLC's were used where there was no matching between SPLC and SMSA.

the firms in our sample to determine the uses of the various terminals, the results were not encouraging. A follow-up telephone survey also failed to provide this information. We therefore had no choice but to derive the variable of terminal density as number of total terminals per ton-mile, referred to as N_4.[5/]

4. "Typical" Firm at Sample Means

Since we utilized a translog functional form for our multiproduct joint cost function, and since translog functions are usually approximated at sample means, it is useful to show the mean value of each variable at this stage (see Table 6.4). A hypothetical carrier with factor prices, operating characteristics and network characteristics at these sample mean values is referred to hereafter as a "typical" or "mean" firm. A typical firm is useful in examining the costs and technology of the trucking industry since trucking production is nonhomothetic, and therefore cannot be generalized.

[5/] Route-miles are not available for four-fifths of our sample.

Table 6.4 Notation of Variables and Associated Mean Values*

Notation	Variable	Mean Value
w_1	Labor price (\$/employee)	17246.3704
w_2	Fuel price (\$/gallon)	0.5932
w_3	Equipment capital price (price index)	10664.0506
w_4	Price of "other" (price index)	4.5676
w_5	Purchased transportation price (price index)	1.3271
N_1	1-Gamma	0.9575
N_2	1-Chi	0.9730
N_3	Indirect Routing Index	1.2391
N_4	Terminal density (ton-miles/terminal)	11446512.1708
t_{11}	Standard deviation of ton-miles for LTL ton-miles with length of haul < 250 miles†	205076.8399
t_{12}	Standard deviation of length of haul for LTL ton-miles with length of haul < 250 miles (miles)	61.1179
t_{21}	Shipment size for LTL ton-miles with length of haul 250-500 miles (tons/shipment)	0.4094
t_{31}	Traffic distribution rate for LTL ton-miles with length of haul 1000-1500 miles	0.8860
t_{32}	Traffic distribution rate for LTL ton-miles with length of haul over 1500 miles	0.9137
t_{41}	Standard deviation of ton-miles for TL ton-miles†	1175152.5095
t_{42}	Standard deviation of length of haul for TL ton-miles (miles)	277.1969
y_1	LTL ton-miles with length of haul < 250 miles†	15590995.9905
y_2	LTL ton-miles with length of haul 250-500 miles†	42549581.6857
y_3	LTL ton-miles with length of haul over 500 miles†	227638713.9048
y_4	TL ton-miles†	360158131.1429

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*Variables not included in the final model specification are not shown.

† Unit: ton-miles

II. Model Specification

We use a translog functional form to specify the general multi-product cost function and its associated hedonic output functions:

$$\begin{aligned}
\ln C(\Psi,W;N,Q) = {} & \alpha_0 + \sum_i \alpha_i \ln \psi_i + \sum_j \beta_j \ln w_j + \sum_k \gamma_k \ln N_k + \sum_h \delta_h \ln Q_h \\
& + \tfrac{1}{2}\Big(\sum_i \sum_s A_{is} \ln \psi_i \ln \psi_s + \sum_j \sum_\ell B_{j\ell} \ln w_j \ln w_\ell \\
& + \sum_k \sum_q C_{kq} \ln N_k \ln N_q + \sum_h \sum_p D_{hp} \ln Q_h \ln Q_p\Big) \\
& + \sum_i \sum_j E_{ij} \ln \psi_i \ln w_j + \sum_i \sum_k F_{ik} \ln \psi_i \ln N_k \\
& + \sum_i \sum_h G_{ih} \ln \psi_i \ln Q_h + \sum_j \sum_k H_{jk} \ln w_j \ln N_k \\
& + \sum_j \sum_h I_{jh} \ln w_j \ln Q_h + \sum_k \sum_h J_{kh} \ln N_k \ln Q_h + \varepsilon
\end{aligned} \tag{6.3}$$

$$\begin{aligned}
\ln\psi_i = {} & \ln y_i + \sum_k a_{ik} \ln t_{ik} + \sum_h b_{ih} \ln d_{ih} \\
& + \tfrac{1}{2}\Big(\sum_k \sum_\ell c_{ik\ell} \ln t_{ik} \ln t_{i\ell} + \sum_h \sum_j e_{ihj} \ln d_{ih} \ln d_{ij}\Big) \\
& + \sum_k \sum_h f_{ikh} \ln t_{ik} \ln d_{ih}
\end{aligned} \tag{6.3a}$$

where ε is a disturbance. Eq. (6.3a) is treated as an identity equation. All variables are measured as deviations from their points of approximation, which are taken as the sample means.

Eqs. (6.3) and (6.3a) are estimated jointly with the factor share equations implied by Shephard's lemma:

$$SR_j = \frac{\partial \ln C}{\partial \ln w_j} = \beta_j + \sum_{\ell} B_{j\ell} \ln w_{\ell} + \sum_{i} E_{ji} \ln \psi_i$$

$$+ \sum_{k} H_{jk} \ln N_k + \sum_{h} I_{jh} \ln Q_h + \eta_j \qquad (6.4)$$

where SR_j is the share of factor j and η_j is the associated disturbance.

The following symmetry conditions should be satisfied in Eqs. (6.3), (6.3a), and (6.4):

$$\begin{aligned} A_{is} &= A_{si} \quad , \quad \forall\ i,s \\ B_{j\ell} &= B_{\ell j} \quad , \quad \forall\ j,\ell \\ C_{kq} &= C_{qk} \quad , \quad \forall\ k,q \\ D_{hp} &= D_{ph} \quad , \quad \forall\ h,p \end{aligned} \qquad (6.5)$$

Cost minimization requires that Eq. (6.3) be homogeneous of degree 1 in factor prices, resulting in the following coefficient restrictions:

$$\sum_{j} \beta_j = 1$$

$$\sum_{j} B_{j\ell} = 0 \quad , \quad \forall\ \ell$$

$$\sum_j E_{ij} = 0 \quad , \quad \forall\, i \tag{6.5a}$$

$$\sum_j H_{jk} = 0 \quad , \quad \forall\, k$$

$$\sum_j I_{jh} = 0 \quad , \quad \forall\, h$$

Although the above coefficient restrictions substantially reduce the number of parameters to be estimated, there are still 108 parameters to be estimated using the above specification. It is possible, however, to reduce the number of estimated parameters still further, by restricting the hedonic output functions (Eq. (6.3a)) to be Cobb-Douglas, as in previous empirical studies.[6] That is,

$$c_{ik} = 0 \quad , \quad \forall\, i,k,$$

$$e_{ihj} = 0 \quad , \quad \forall\, i,h,j \tag{6.6}$$

$$f_{ikh} = 0 \quad , \quad \forall\, i,k,h$$

With these additional restrictions, there are now a total of 98 parameters to be estimated. While still a large number, they can be handled by existing estimation procedures.[7]

Since the factor shares must sum to one, the factor share equations are not independent but must satisfy the following restrictions in the parameters and disturbances:[8]

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[6] Spady and Friedlaender (1978), Wang Chiang (1979), and Friedlaender, Spady, and Wang Chiang (1981).

[7] The program used to estimate this cost function is based upon the translog estimation package written by Spady and Snow (1978). Some modifications have been made. This program can be made available upon request.

[8] Berndt and Wood (1975).

$$\sum_j \beta_{jt} = 1 \quad , \quad \forall t \tag{6.7}$$

$$\sum_j \eta_{jt} = 0 \quad , \quad \forall t \quad ,$$ where t is the subscript for an observation.

Thus, the variance-covariance matrix of η_j's is singular. Moreover, there is reason to believe that the disturbances among both the cost and factor share equations are correlated. We thus specify that (ε, η_j's) are multivariately, normally distributed and estimate Eqs. (6.3) — (6.6) simultaneously using the full information maximum likelihood (FIML) procedures. To get consistent estimates, all but one of the factor share equations are included in the system of equations.[9/] Maximum likelihood estimators are numerically invariant to the dropping of any one equation; it does not matter which equation is omitted, and we omit the purchased transportation factor share equation.

III. Estimation Results

Tables 6.5 and 6.6 show the estimated coefficients and associated standard errors for the translog cost function and hedonic output functions. The specific definitions of the variables used in our analysis are given as follows.[10/]

[9/] See Appendix D for a description of FIML estimation procedures.

[10/] In the final estimation, parameters were omitted that were shown to be consistently statistically insignificant (as determined by t-tests and likelihood ratio tests).

C = Total annual costs in dollars, i.e., the sum of (1) labor costs, (2) fuel expenditures and fuel taxes, (3) capital costs for revenue equipment, (4) "other" expenditures, and (5) purchased transportation expenditures

w_1 = Labor price index in dollars per employee, including all fringes and benefits

w_2 = Fuel price in dollars per gallon of gasoline, including fuel taxes

w_3 = Factor price of capital for revenue equipment

w_4 = Factor price of other expenditures not elsewhere classified

w_5 = Price index for purchased transportation equipment and services

SR_1 = Factor share of labor, defined as total labor costs divided by total costs

SR_2 = Factor share of fuel, defined as total fuel costs (including fuel taxes) divided by total costs

SR_3 = Factor share of equipment capital, defined as total capital costs on equipment divided by total costs

SR_4 = Factor share of "other" costs, defined as other expenditures divided by total costs

SR_5 = Factor share of purchased transportation, defined as total costs of purchased transportation divided by total costs

y_1 = Type 1 output, defined as total LTL ton-miles with length of haul less than 250 miles

y_2 = Type 2 output, defined as total LTL ton-miles with length of haul of 250 $\sim$ 500 miles

y_3 = Type 3 output, defined as total LTL ton-miles with length of haul over 500 miles

y_4 = Type 4 output, defined as total TL ton-miles

ψ_1 = Hedonically adjusted y_1

ψ_2 = Hedonically adjusted y_2

ψ_3 = Hedonically adjusted y_3

ψ_4 = Hedonically adjusted y_4

t_{11} = Standard deviation of ton-miles for LTL shipments with length of haul less than 250 miles

t_{12} = Standard deviation of length of haul for LTL shipments with length of haul less than 250 miles

t_{21} = Average shipment size for LTL shipments with length of haul between 250 and 500 miles

$$t_{31} = (1 - \frac{\text{LTL ton-miles with length of haul 1000 - 1500 miles}}{\text{LTL ton-miles with length of haul over 500 miles}})$$

$$t_{32} = (1 - \frac{\text{LTL ton-miles with length of haul greater than 1500 miles}}{\text{LTL ton-miles with length of haul over 500 miles}})$$

(Both t_{31} and t_{32} are used to reflect further differences in y_3 in terms of traffic distribution by distance.)

t_{41} = Standard deviation of ton-miles for TL shipments

t_{42} = Standard deviation of length of haul for TL shipments

N_1 = Global network connectivity measure, defined as (1-Gamma index)

N_2 = Global network density measure, defined as (1-Chi index)

N_3 = Indirect routing index

N_4 = Terminal density measure, defined as ton-miles per terminal

Table 6.5 Coefficient Estimates and Statistics for the Cost and Factor Share Equations

COEFFICIENT	VARIABLE*	VALUE	STANDARD ERROR
α_0	Constant	19.1176	0.0620
α_1	Ψ_1	0.1022	0.0453
α_2	Ψ_2	0.0856	0.0771
α_3	Ψ_3	0.3349	0.0466
α_4	Ψ_4	0.4789	0.0671
β_1	w_1	0.6357	0.0098
β_2	w_2	0.0681	0.0024
β_3	w_3	0.0187	0.0011
β_4	w_4	0.2141	0.0042
β_5	w_5	0.0634	0.0114
γ_1	N_1	2.6929	2.8253
γ_2	N_2	-6.6476	4.9723
γ_3	N_3	1.0230	0.7171
γ_4	N_4	-0.0290	0.8157
A_{11}	Ψ_1^2	-0.0278	0.0386
A_{12}	$\Psi_1\Psi_2$	-0.0481	0.0458
A_{13}	$\Psi_1\Psi_3$	-0.0890	0.0190
A_{14}	$\Psi_1\Psi_4$	0.0852	0.0433
A_{22}	Ψ_2^2	0.1460	0.0927
A_{23}	$\Psi_2\Psi_3$	0.0296	0.0329
A_{24}	$\Psi_2\Psi_4$	-0.1496	0.0921
A_{33}	Ψ_3^2	0.0336	0.0129

Table 6.5, continued

COEFFICIENT	VARIABLE*	VALUE	STANDARD ERROR
A_{34}	$\psi_3\psi_4$	0.0099	0.0276
A_{44}	ψ_4^2	0.2670	0.0891
B_{11}	w_1	0.0774	0.0084
B_{12}	w_1w_2	-0.0443	0.0049
B_{13}	w_1w_3	-0.0097	0.0029
B_{14}	w_1w_4	-0.0114	0.0040
B_{15}	w_1w_5	-0.0120	0.0050
B_{22}	w_2^2	0.0499	0.0054
B_{23}	w_2w_3	-0.0040	0.0026
B_{24}	w_2w_4	-0.0017	0.0011
B_{25}	w_2w_5	0.0001	0.0012
B_{33}	w_3^2	0.0161	0.0022
B_{34}	w_3w_4	-0.0015	0.0007
B_{35}	w_3w_5	-0.0009	0.0006
B_{44}	w_4^2	0.0050	0.0034
B_{45}	w_4w_5	0.0097	0.0026
B_{55}	w_5^2	0.0031	0.0059
C_{33}	N_3^2	11.4786	6.8264
C_{34}	N_3N_4	-2.4903	0.8781
C_{44}	N_4^2	0.1957	0.1342
E_{11}	ψ_1w_1	0.0026	0.0064
E_{12}	ψ_1w_2	-0.0024	0.0016
E_{13}	ψ_1w_3	-0.0002	0.0007
E_{15}	ψ_1W_5	-0.0001	0.0078

Table 6.5, continued

COEFFICIENT	VARIABLE*	VALUE	STANDARD ERROR
E_{21}	$\psi_2 w_1$	0.0544	0.0105
E_{22}	$\psi_2 w_2$	0.0074	0.0027
E_{23}	$\psi_2 w_3$	0.0015	0.0012
E_{25}	$\psi_2 w_5$	-0.0633	0.0128
E_{31}	$\psi_3 w_1$	-0.0019	0.0040
E_{32}	$\psi_3 w_2$	0.0010	0.0009
E_{33}	$\psi_3 w_3$	-0.0004	0.0004
E_{34}	$\psi_3 w_4$	0.0015	0.0016
E_{35}	$\psi_3 w_5$	-0.0002	0.0048
E_{41}	$\psi_4 w_1$	-0.0326	0.0104
E_{42}	$\psi_4 w_2$	-0.0056	0.0025
E_{43}	$\psi_4 w_3$	-0.0007	0.0010
E_{44}	$\psi_4 w_4$	-0.0071	0.0043
E_{45}	$\psi_4 w_5$	0.0460	0.0120
F_{13}	$\psi_1 N_3$	1.0386	0.4037
F_{14}	$\psi_1 N_4$	-0.0402	0.0735
F_{23}	$\psi_2 N_3$	-2.1168	0.8286
F_{24}	$\psi_2 N_4$	-0.1084	0.1377
F_{33}	$\psi_3 N_3$	0.4782	0.2421
F_{34}	$\psi_3 N_4$	0.0555	0.0317
F_{43}	$\psi_4 N_3$	0.8263	0.8773
F_{44}	$\psi_4 N_4$	-0.2108	0.1196
H_{13}	$w_1 N_3$	0.1576	0.0985
H_{14}	$w_1 N_4$	0.0112	0.0138

Table 6.5, continued

COEFFICIENT	VARIABLE*	VALUE	STANDARD ERROR
H_{23}	w_2N_3	0.0103	0.0232
H_{24}	w_2N_4	0.0086	0.0032
H_{33}	w_3N_3	-0.0061	0.0108
H_{43}	w_4N_3	0.0851	0.0478
H_{44}	w_4N_4	0.0025	0.0065
H_{53}	w_5N_3	-0.2469	0.1106
H_{54}	w_5N_4	-0.0222	0.0153

FINAL LOG OF LIKELIHOOD FUNCTION = 1148.214

NUMBER OF OBSERVATIONS = 105

R^2: COST FUNCTION = 0.976
LABOR EQUATION = 0.354
FUEL EQUATION = 0.144
EQUIP. CAPITAL EQUATION = 0.389
"OTHER" EQUATION = 0.015
PURCHASED TRANS. EQUATION = 0.322

RMSE: COST FUNCTION = 0.2188
LABOR EQUATION = 0.0621
FUEL EQUATION = 0.0144
EQUIP. CAPITAL EQUATION = 0.0063
"OTHER" EQUATION = 0.0296
PURCHASED TRANS. EQUATION = 0.0704

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*We have omitted "ℓn" for convenience.

Table 6.6 Coefficient Estimates and Statistics for the Hedonic Output Functions

COEFFICIENT	VARIABLE[*]	VALUE	STANDARD ERROR
a_{11}	t_{11}	0.0534	0.1174
a_{12}	t_{12}	1.9327	0.4448
a_{21}	t_{21}	0.1455	0.3084
a_{31}	t_{31}	-0.5236	0.4368
a_{32}	t_{32}	-0.4327	0.3256
a_{41}	t_{41}	0.0084	0.0978
a_{42}	t_{42}	-0.8720	0.2367

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[*] We have omitted "ℓn" for convenience.

A. Nonhomotheticities

Input-output separability implies that the marginal rates of transformation between outputs be independent of factor intensities or factor prices. Under the translog specification of the cost function given in Eq. (6.3), separability implies the following coefficient restriction:

$$E_{ij} = 0 \quad , \quad \forall\, i,j \tag{6.8}$$

Stronger conditions for separability require also that the interaction terms between factor prices and aggregate network and operating characteristics be zero, i.e.,

$$\begin{aligned} H_{jk} &= 0 \quad , \quad \forall\, j,k \\ I_{jh} &= 0 \quad , \quad \forall\, j,h \end{aligned} \tag{6.9}$$

From Table 6.5 one can see that the estimates of the E_{ij}'s, H_{jk}'s, and I_{jh}'s are, in general statistically different from zero. The hypothesis of input-output separability is thus rejected even under the weak conditions of Eq. (6.8). This reinforces the finding in previous studies that trucking production is nonhomothetic and any attempts to model trucking technology by a homothetic function such as the Cobb-Douglas function will lead to biased results. Since the technology specified by Eq. (6.3) is nonhomothetic, global characterizations of returns to scale are inappropriate.

B. Factor Utilization

As shown in Table 6.5; the goodness-of-fit measures for the factor share equations are generally low, ranging from 0.015 to 0.389. Although R^2 is merely a descriptive statistic in simultaneous equation systems, the low value of R^2 in the factor share equations still indicates that the factor shares have not been explained very well. This is especially true for "other" expenditures, whose R^2 was 0.015. Since, however, "other" expenditures represent the residual of total costs not elsewhere classified, there is doubtless some aggregation error associated with this variable, which vitiates the explanatory power of the independent variables.

For a translog cost function, the Allen partial elasticities of substitution (APES) between inputs i and j, σ_{ij}, and the partial price elasticities of input demand, e_{ij}, can be written as:[11]

$$\begin{aligned}
\sigma_{ii} &= \frac{B_{ii} - \hat{SR}_i}{\hat{SR}_i^2} + 1 \\
\sigma_{ij} &= \frac{B_{ij}}{\hat{SR}_i \hat{SR}_j} + 1 \quad , \; i \neq j \\
e_{ii} &= \hat{SR}_i + \frac{B_{ii}}{\hat{SR}_i} - 1 \\
e_{ij} &= \hat{SR}_j + \frac{B_{ij}}{\hat{SR}_i} \quad , \; i \neq j
\end{aligned} \tag{6.10}$$

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[11] See Berndt and Wood (1975) for the derivation of these elasticities for a translog cost function.

where $\hat{SR}_i$ is the fitted factor share for the i^{th} factor.

Table 6.7 presents these elasticities calculated at the sample mean. The demands for purchased transportation and "other" expenditures are most sensitive to price, with their own price elasticities being approximately -0.89 and -0.76, respectively. The relatively high own price elasticity of purchased transportation is not surprising since firms treat purchased transportation as a residual source of equipment and therefore adjust their demand for rented transportation vehicles and purchased transportation services in response to price changes, at least in the short run. The own price elasticities for the other factors are relatively inelastic, ranging from -0.122 (equipment capital) to -0.2426 (labor). This is to be expected in view of the relative fixidity of equipment and the strength of union agreements. The elasticities of substitution indicate that labor and equipment capital are substitutes with an elasticity of substitution of approximately 0.19. Labor is also a substitute for purchased transportation and the "other" factor. The relatively high elasticity of substitution (1.019) between fuel and purchased transportation is interesting since it reflects two conflicting forces. Fuel can be a substitute for or a complement to purchased transportation since the latter includes rented transportation equipment as well as purchased transportation services. Rented transportation equipment requires explicit fuel purchases and is therefore a complement while purchased transportation services do not, and are therefore substitutes. Our results indicate that equipment rentals play a relatively small role in purchased transportation services, with a high degree of substitutability between fuel and purchased transportation. It is also

Table 6.7 Factor Demand Elasticities and Allen-Uzawa Partial Elasticities of Substitution of Common Carriers of General Commodities[*]

	Labor	Fuel	Equipment Capital	"Other"	Purchased Transportation
Labor		-0.0224 (0.1284)	0.1855 (0.2563)	0.9160 (0.0297)	0.7024 (0.1231)
Fuel			-2.1437 (2.0250)	0.8821 (0.0735)	1.0188 (0.2860)
Equipment Capital				0.6248 (0.1929)	0.2617 (0.5453)
"Other"					1.7116 (0.2579)
Own Price Elasticity	-0.2426 (0.0165)	-0.1991 (0.0851)	-0.1222 (0.1316)	-0.7625 (0.0173)	-0.8873 (0.0943)

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[*] Standard errors in parentheses

interesting to note that fuel and capital equipment are estimated to be strong complements with an elasticity of substitution as large as -2.14.

The factor share equations (Eq. (6.4)) indicate that factor shares are affected by factor prices, levels of hedonically adjusted output, and network/operating characteristics. To identify the influence of the composition of output upon factor utilization, we evaluate these effects for a "typical" firm facing mean factor prices and network characteristics, so that the terms in factor prices and network variables vanish from the share equation.

The interaction terms between outputs and factor prices, as shown in Table 6.8, are generally statistically significant and indicate that the level of composition of output has important effects on factor utilization. For example, in the labor share equation, E_{11} and E_{21} are estimated to be positive while E_{31} and E_{41} are estimated to be negative, indicating that short-haul LTL movements are more labor-intensive than TL and long-haul LTL movements. The negative signs of E_{12} amd E_{42} in the fuel share equations suggest that TL and very short-haul LTL operations are less fuel-intensive due to fewer terminal operations. The same effects are indicated for the utilization of capital equipment. These follow our expectations since TL and short-haul LTL operations generally involve direct service with no terminal operations. The E_{ij}'s for purchased transportation utilization are estimated to be positive for TL operations and negative for LTL operations; TL operations are less fixed in terms of vehicle dispatching and therefore are more likely to utilize hired transportation equipment.

Table 6.8 Factor Share Equations at Mean Factor Prices and Network Characteristics*

COEFFICIENT	VARIABLE	1 LABOR	2 FUEL	3 EQUIPMENT CAPITAL	4 OTHER	5 PURCHASED TRANSPORTATION
β_j	constant	0.6357 (0.0098)	0.0681 (0.0024)	0.0187 (0.0011)	0.2141 (0.0042)	0.0634 (0.0114)
E_{1j}	$\ell n\Psi_1$	0.0026 (0.0064)	-0.0024 (0.0016)	-0.0002 (0.0007)	—	-0.0001 (0.0078)
E_{2j}	$\ell n\Psi_2$	0.0544 (0.0105)	0.0074 (0.0027)	0.0015 (0.0012)	—	-0.0633 (0.0128)
E_{3j}	$\ell n\Psi_3$	-0.0019 (0.0040)	0.0010 (0.0009)	-0.0004 (0.0004)	0.0015 (0.0016)	-0.0002 (0.0048)
E_{4j}	$\ell n\Psi_4$	-0.0326 (0.0104)	-0.0056 (0.0025)	-0.0007 (0.0010)	-0.0071 (0.0043)	0.0460 (0.0120)

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*Standard errors in parentheses

$$SR_j = \frac{\partial\, \ell n\, C}{\partial\, \ell n\, w_j} = \beta_j + \sum_i E_{ji}\, \ell n\, \psi_i \qquad (6.4c)$$

C. The Impact of Network Effects upon Costs and Factor Demands

Since the evidence obtained here suggests that trucking technology is nonhomothetic, the relationship between costs and network characteristics cannot be globally characterized. Thus changes in costs with respect to network characteristics will usually differ depending upon the levels of factor prices, outputs and other variables. The elasticity of cost with respect to network characteristics can be given by the following equation:

$$\frac{\partial \ln C}{\partial \ln N_i} = \gamma_i + \sum_j C_{ij} \ln N_j + \sum_j F_{ij} \ln \psi_j + \sum_j H_{ij} \ln w_j \tag{6.11}$$

At mean factor prices and output levels, this reduces to

$$\frac{\partial \ln C}{\partial \ln N_i} = \gamma_i + \sum_j C_{ij} \ln N_j \tag{6.11a}$$

Thus γ_i reflects the elasticity of cost with respect to global network measure i for a "typical" firm operating at the sample mean, and the term $\sum_j C_{ij} \ln N_j$ measures the additional effects of network characteristics upon costs as they diverge from mean values.

The estimated γ_i's and C_{ij}'s and their standard errors are shown in Table 6.9. We find that network connectivity—N_1, defined as (1 - Gamma index)—has a positive impact on costs, as expected. A higher value of N_1 indicates a lower degree of network connectivity. Thus a firm using a highly connected network would have cost advantages over one using a less connected network. This is to be expected since a highly connected network would enable a firm to utilize its equipment more efficiently. Another measure of network connectivity and configuration is the indirect routing index, N_3. By our definition, a lower value of the indirect routing index indicates a large network with many routes and terminals such that direct routing becomes efficient. The estimated positive elasticity of N_3, 1.023, empirically supports this proposition. Thus economies of network configuration seem to exist for the "typical" firm operating at the sample mean. Moreover, the positive C_{33} coefficient implies that as the indirect routing index increases from the mean, economies of network configuration increase. The existence of economies of network configuration explain why large carriers enjoy a natural advantage over smaller carriers, as surveys have shown: shippers prefer to deal with as few carriers as possible to reduce the chance of loss, delay, or damage from additional handling. Thus the large carrier that operates nationwide with its own fleet has significant advantages over a smaller carrier which must interline with others in order to offer service on a national level.

Table 6.9 Elasticity of Costs with Respect to Network Characteristics at Mean Factor Prices and Output Levels

COEFFICIENT	VARIABLE	N_1 NETWORK CONNECTIVITY	N_2 NETWORK DENSITY	N_3 INDIRECT ROUTING INDEX	N_4 TERMINAL DENSITY
γ_i	Constant	2.6929 (2.8253)	-6.6476 (4.9723)	1.0230 (0.7171)	-0.0290 (0.8157)
C_{i3}	$\ell n N_3$	—	—	11.4786 (6.8264)	-2.4903 (0.8781)
C_{i4}	$\ell n N_4$	—	—	-2.4903 (0.8781)	0.1957 (0.1342)

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*Standard errors in parentheses

$$\frac{\partial \ell n\, C}{\partial \ell n\, N_i} = \gamma_i + \sum_j C_{ij}\, \ell n\, N_j \qquad (6.11a)$$

Conditional on network configuration, a measure of flow density is given by the network density measure N_2. By our definition, a higher value of N_2 implies a network with better routing practices and terminal consolidation. The elasticity of cost with respect to this variable, estimated as approximately -6.65, gives clear evidence of the existence of economies of density. This elasticity remains unchanged for firms with network characteristics varying from mean values, since C_{2j}'s are estimated to be not significantly different from zero.

N_4 measures terminal density, which is defined as ton-miles/terminal. Thus a network with a small value of N_4 involves more terminal operations. As indicated in Chapter Five, this variables has an ambiguous effect upon costs. More terminal operations could imply better routing strategies, but they could also reflect a poorly connected network. The estiamted negative elasticity of -0.0290 suggests that the second effect seems to be dominant. However, as indicated by the positive value of C_{44}, this tendency decreases for firms having ton-miles/terminal greater than mean value. Thus the first effect could possibly predominate for firms with more ton-miles/terminal than a mean firm, holding other variables constant.

The effects of network characteristics upon factor demand can be examined through the elasticity of demand with repepct to network variables. The elasticity of demand for factor i with respect to aggregate network characteristics j is given by:

$$\gamma_j + H_{ij}/\beta_i \qquad (6.12)$$

These elasticities are presented in Table 6.10. One can clearly see that an increase in the variable N_2 holding network configuration unchanged results in input savings in all factors. Thus there are economies of network operation and traffic density, i.e., economies associated with appropriately loading traffic over a given network. Similarly, the elasticities of factor demands with respect to network connectivity and the indirect routing index (N_1 and N_3, respectively) indicate that there are advantages in terms of input requirements for an extensively connected network which has large coverage and an ability to provide direct service between city pairs served by it. This again gives strong evidence of the existence of economies of network configuration. The elasticities of factor demands with respect to terminal density are negative except for fuel. This is reasonable since an increase in the amount of traffic (ton-miles) handled by a terminal involves more indirect routing, which results in more fuel consumption.

D. Economies of Scale

While it is not possible to make global generalizations concerning returns to scale for a nonhomothetic production structure, it is possible to examine returns to scale at the point of approximation. A local measure of multiproduct returns to scale is given by

$$S = 1 \Big/ \sum_i^4 (\alpha_i + \sum_j A_{ij} \ell n \psi_j + \sum_j E_{ij} \ell n w_j + \sum_j F_{ij} \ell n N_j) \qquad (6.13)$$

At the sample mean, this reduces to

$$S = 1/\sum_i \alpha_i \qquad (6.13a)$$

Table 6.10 Elasticities of Factor Demand with Respect to Network Characteristics at Sample Means

	Labor	Fuel	Equipment Capital	Other	Purchased Transportation
N_1 (Network Connectivity)*	2.6929	2.6929	2.6929	2.6929	2.6929
N_2 (Network Density)	-6.6476	-6.6476	-6.6476	-6.6476	-6.6476
N_3 (Indirect Routing Index)	1.2709	1.1742	0.6968	1.4205	-2.8713
N_4 (Terminal Density)	-0.0114	0.0973	-0.0290	-0.0173	-0.3792

*N_1 = (1 - Gamma Index). A higher value of N_1 indicates a less connected network.

This scale economy is estimated to be 0.9984 with a standard error of 0.0679. Thus for typical firms facing mean factor prices and mean network characteristics, the technology exhibits constant returns to scale. There would be no cost advantages to producing more output in fixed proportions, holding factor prices and network characteristics unchanged.

Economies of scale are a sufficient condition for subadditivity along a ray and the latter is a necessary condition for a natural monopoly. Scale economies are a stronger condition for ray subadditivity than declining ray-average costs, as indicated in Chapter Four. Thus this empirical finding of constant returns to scale casts doubt on the possibility that the trucking industry (as exemplified in our sample) would behave as a natural monopoly in the absence of regulation.

This raises the question of explaining the observed increasing concentration among general-commodity carriers. One proposition would be that although there are no product-specific economies of scale in this segment of the trucking industry, there could be economies of scope due to the existence of economies of network configuration and network density. Indeed, the previous analysis of the impact of network effects upon costs substantiates this hypothesis. Nevertheless, to explore this question further, it is useful to analyze the relationship between costs and the composition of output to see to what extent these cost differences are due to output effects.

1. Transray Convexity

As discussed in Chapter Four, transray convexity refers to the impact that the composition of output has upon costs. Simply stated, the existence of transray convexity implies that a single firm producing a number of outputs jointly can produce the same output bundle more cheaply than a number of specialized firms.

A formal analysis of the extence of transray convexity requires the utilization of the Hessian matrix. A Hessian matrix of the cost function contains the second derivatives of the cost with respect to outputs:

$$H = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} \\ C_{21} & C_{22} & C_{23} & C_{24} \\ C_{31} & C_{32} & C_{33} & C_{34} \\ C_{41} & C_{42} & C_{43} & C_{44} \end{bmatrix} \tag{6.14}$$

where $C_{ij} = \partial C/\partial\psi_i\partial\psi_j$. Evaluated at the point of approximation, this yields for our sample

$$\bar{H} = 10^{-6} x \begin{bmatrix} -0.131044 & -0.015799 & -0.004110 & 0.006363 \\ -0.015799 & 0.009963 & 0.001603 & -0.001888 \\ -0.004110 & 0.001603 & -0.000973 & 0.000553 \\ 0.006363 & -0.001888 & 0.000553 & 0.000036 \end{bmatrix} . \tag{6.14a}$$

(The bar over the H indicates evaluation of the variable at the sample mean.)

This matrix is not positive—definite since its diagonal elements are not all positive. Therefore, the cost surface is not convex with respect to output. In addition, weak complementarity between ψ_i and ψ_j $(i \neq j)$ requires that each C_{ij} be nonpositive, and this condition is not satisfied for all product pairs either. Thus our Hessian matrix does not imply that costs are globally transray-convex at the point of approximation. However, since cost convexity and weak cost complementarity everywhere are merely <u>sufficient</u> conditions for transray convexity, the failure of both tests does not mean that cross sectional cost advantages do not exist, since transray convexity may still exist among output pairs.

The cost function can be transray-convex along a hyperplane defined by $\sum_i u_i y_i = v$, $\forall u_i > 0$ if the corresponding bordered Hessian has border-preserving principal minors all of whose determinants are nonpostiive, where the u's represent arbitrary output shares. In the four-output case, these conditions become

$$\det \begin{vmatrix} C_{11} & u_1 \\ u_1 & 0 \end{vmatrix} \leq 0 \qquad (6.15a)$$

$$\det \begin{vmatrix} C_{11} & C_{12} & u_1 \\ C_{12} & C_{22} & u_2 \\ u_1 & u_2 & 0 \end{vmatrix} \leq 0 \qquad (6.15b)$$

$$\det \begin{vmatrix} C_{11} & C_{12} & C_{13} & u_1 \\ C_{12} & u_{22} & C_{23} & u_2 \\ C_{13} & C_{23} & C_{33} & u_3 \\ u_1 & u_2 & u_3 & 0 \end{vmatrix} \leq 0 \qquad (6.15c)$$

$$\det \begin{vmatrix} C_{11} & C_{12} & C_{13} & C_{14} & u_1 \\ C_{12} & C_{22} & C_{23} & C_{24} & u_2 \\ C_{13} & C_{23} & C_{33} & C_{34} & u_3 \\ C_{14} & C_{24} & C_{34} & C_{44} & u_4 \\ u_1 & u_2 & u_3 & u_4 & 0 \end{vmatrix} \leq 0 \qquad (6.15d)$$

Condition (6.15a) is always satisfied for any C_{ii}. Conditions (6.15b) — (6.15d) need some examination since the values of these determinants depend not only on C_{ij}'s but also on u_i's, by which a hyperplane is defined. As we indicated earlier in Chapter Four, transray convexity requires the conditions to be satisfied along only one hyperplane implying that any one set of positive u_i's which satisfies the conditions (6.15b) — (6.15d) would be sufficient to indicate that the cost function is transray-convex. Although there is no systematic way to identify a set of critical u_i's when there are many outputs, it is not difficult to examine the condition when there are only two outputs. As indicated by Baumol, Panzar and Willig (1979), one of the following situations is sufficient to guarantee that condition (6.15b) is satisfied:

$$\begin{aligned} &C_{11} \geq 0,\ C_{22} \geq 0,\ C_{12} = C_{21} \leq 0 \\ &C_{11} \leq 0,\ C_{22} \leq 0,\ C_{12} = C_{21} \leq 0,\ C_{12} \leq -\sqrt{C_{11}C_{22}} \end{aligned} \tag{6.16}$$

Thus we can test for the existence of transray convexity between product pairs. By doing so for all product pairs, useful information concerning overall transray behavior can be obtained.

Testing the conditions of Eq. (6.16) for each product pair evaluated at sample means yields

$$\begin{aligned} &\cdot\ C_{11} < 0,\ C_{22} > 0,\ C_{12} < 0,\ C_{11}C_{22} - C_{12}^2 < 0 \\ &\cdot\ C_{11} < 0,\ C_{33} < 0,\ C_{13} < 0,\ C_{11}C_{33} - C_{13}^2 > 0 \\ &\cdot\ C_{11} < 0,\ C_{44} > 0,\ C_{14} > 0,\ C_{11}C_{44} - C_{14}^2 < 0 \\ &\cdot\ C_{22} > 0,\ C_{33} > 0,\ C_{23} > 0,\ C_{22}C_{33} - C_{23}^2 < 0 \\ &\cdot\ C_{22} > 0,\ C_{44} > 0,\ C_{24} < 0,\ C_{22}C_{44} - C_{44}^2 < 0 \\ &\cdot\ C_{33} < 0,\ C_{44} > 0,\ C_{34} > 0,\ C_{33}C_{44} - C_{34}^2 < 0 \end{aligned} \tag{6.17}$$

Thus, costs are transray-convex between outputs 2 and 4 but not between the other output pairs.[12] Therefore we can conclude that the test for overall transray convexity does not hold.

To summarize, a natural monopoly requires subadditivity along a given ray as well as subadditivity with respect to the composition of output. Strict subadditivity along a ray means that a single firm can produce a given bundle of output at a lower cost than many firms each producing smaller output levels with the same output proportions. Cross sectional subadditivity means that a single firm can produce a bundle of output more cheaply than many firms, each producing a subset of that bundle at the same level. Unfortunately, the tests for subadditivity provide sufficient, but not necessary conditions: a sufficient condition for ray subadditivity is increasing returns to scale, while a sufficient condition for cross sectional subadditivity is transray convexity. Our estimate of multiproduct returns to scale is 0.9984 with a standard error of 0.0679, indicating that there are no global scale economies in the trucking industry, at least at the sample mean. Furthermore, the tests for transray convexity between product pairs also suggest that it is unlikely that transray convexity exists for the output vector. Therefore, our empirical results do not provide any evidence that the trucking industry is subject to natural monopoly in the absence of regulation. Of course, this does not imply that the trucking industry can never be a natural monopoly because scale economies and transray convexity are sufficient but not necessary conditions for cost subadditivity.

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[12] With some output pairs undetermined.

Hence, in principle it is possible for natural monopoly and full cost subadditivity to exist even though we do not find evidence of ray or cross sectional subadditivity. Nevertheless, the estimated scale economy of 0.998 and the lack of evidence of transray convexity strongly suggest that global subadditivity does not exist.

2. Product-Specific Scale Economies

This section presents a more detailed examination of the technology of production in the trucking industry. We will examine costs and scale economies output by output and investigate whether economies of joint production exist.

It is reasonable to assume that trucking production involves common fixed costs rather than product-specific fixed costs for two reasons: vehicles, labor and fuel are common inputs and can easily be transferred among markets; and fixed facilities like terminals and platforms are used for all types of output. In fact, trucking operations involve a dynamic routing of vehicles over a network to handle different types of freight (see Figure 6.1), and thus the costs of terminals, administration, equipment, etc., are common to all outputs and cannot be allocated to specific shipments. The problem, therefore, is to estimate the amount of the common fixed costs. In principle the common fixed cost element can be estimated as the costs that are incurred when all output levels are zero. However, in a translog or other log-linear cost formulation this approach does not work since $C(0) = 0$. One solution to this problem is to estimate the costs at a small level of output, Y^*, and calculate $C^* = C(Y^*)$. Then C^* would primarily represent common fixed costs. Experimental analysis suggests defining Y^* as 10 percent

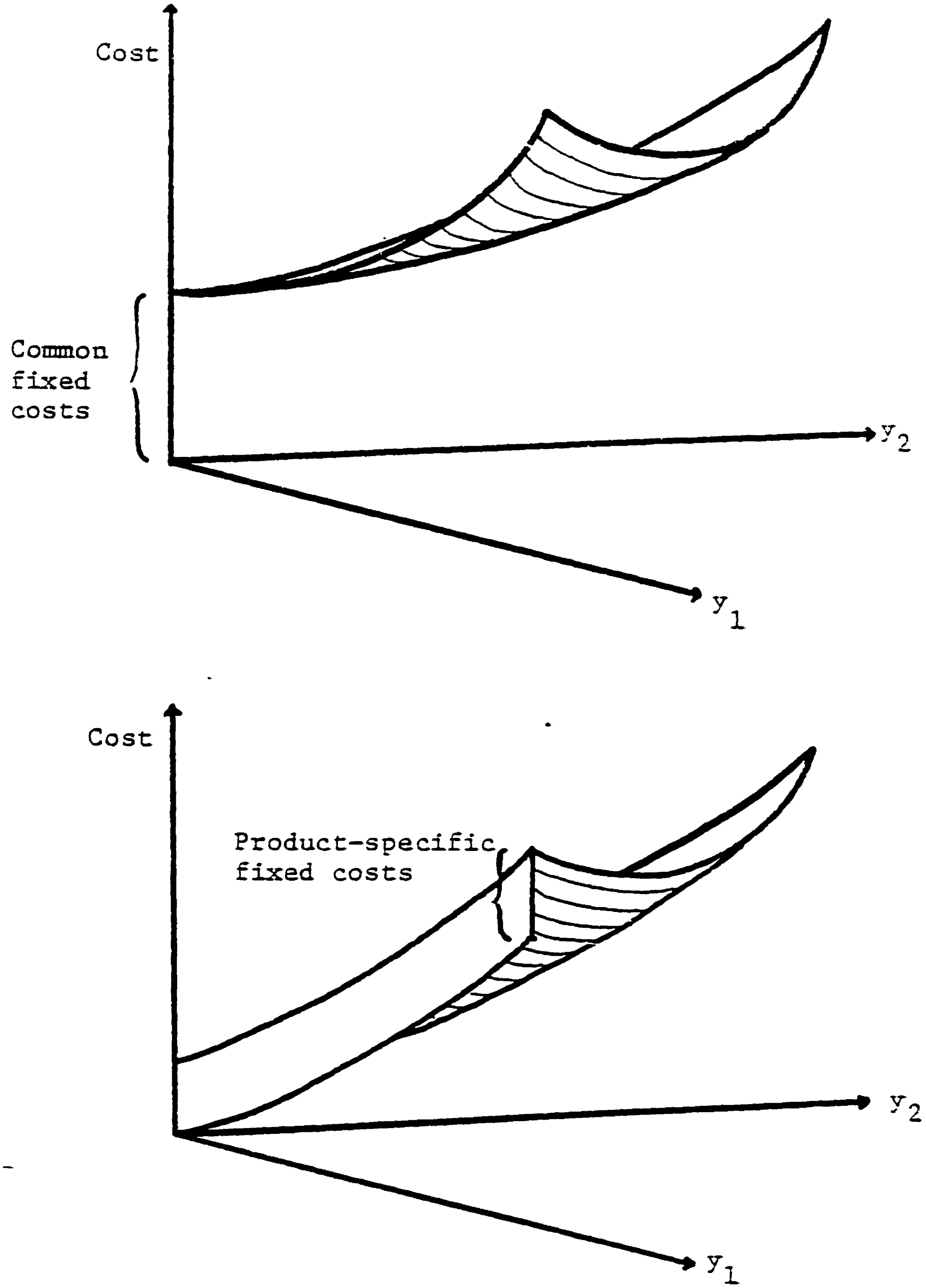

Figure 6.1 Common Fixed Costs vs. Product-Specific Fixed Costs

of Y at the sample mean to arrive at the common fixed costs.

Recall that product-specific scale economies for output i, S_i, are defined as

$$S_i(Y,W;t) = \frac{AIC_i(Y,W;t)}{C_i(Y,W;t)} \quad . \qquad \begin{array}{c}(4.10)\\ \text{repeated}\end{array}$$

where C_i is marginal cost and AIC_i is average incremental cost. With the estimated common fixed costs, it is straightforward to derive total and average incremental costs, as defined in Eqs. (4.8) and (4.9). Tables 6.11 — 6.14 give the estimated total costs, average incremental costs and marginal costs for each type of product at various levels of output, including the sample mean.

Generally speaking, both average incremental and marginal costs for product 1, short-haul LTL freight, are large in magnitude and declining throughout the range of production.[13/] By contrast, they are steadily increasing throughout for product 2, intermediate-haul LTL freight. The average incremental cost curve is an inverted-U-shape for long-haul LTL freight, and U-shaped for TL movements. Note that a flexible cost function behaves best at the point of approximation—in our case, the sample mean. As shown in Table 6.15, for a typical firm with mean characteristics, the marginal costs are 1.746, 0.536, 0.392, and 0.354 in dollars/ton-mile for y_1, y_2, y_3, and y_4, respectively. These figures are generally reasonable and consistent with expectations.[14/]

[13/] Note that it is possible to have negative average incrmental cost or marginal costs in a multiproduct environment.

[14/] However, the cost per ton-mile of $1.746 for short-haul LTL traffic is somewhat high. Nevertheless, since our smaple consisted of large carriers whose traffic hauls were generally greater than 250 miles, the output levels of LTL traffic under 250 miles were generally low and unevenly distributed. Thus the estimate of marginal costs for short-haul LTL traffic is probably biased upwards.

Table 6.11 Average and Marginal Costs for Output 1

(y_1 = LTL < 250 miles)

Ton-Miles (millions)	Total Costs* ($ millions)	Specific Average Costs** ($/ton-mile)	Average Incremental Costs ($/ton-mile)	Marginal Costs ($/ton-mile)
5	228.818	45.764	9.425	6.124
10	253.217	25.322	4.152	2.900
15.591†	266.430	17.089	4.237	1.746
30	281.482	9.383	3.326	0.788
40	286.198	7.155	2.613	0.544
50	288.992	5.780	2.146	0.403
100	292.630	2.926	1.109	0.148
150	291.148	1.941	0.730	0.076
200	288.497	1.442	0.534	0.045
300	282.582	0.942	0.336	0.019

---

*Holding other outputs at their sample means.

**Specific average costs is defined as total costs divided by ton-miles

†Sample mean

Table 6.12 Average and Marginal Costs for Output 2
(y_2 = LTL 250-500 miles)

Ton-Miles (millions)	Total Costs[*] ($ millions)	Specific Average Costs[**] ($/ton-mile)	Average Incremental Costs ($/ton-mile)	Marginal Costs ($/ton-mile)
10	319.661	31.966	-15.472	-4.021
20	271.422	13.571	-10.148	-0.334
30	263.227	8.774	-7.038	0.304
40	265.172	6.629	-5.230	0.508
42.5496[†]	266.430	6.262	-4.159	0.536
100	318.903	3.189	-1.555	0.671
150	374.196	2.495	-0.668	0.673
200	431.530	2.158	-0.214	0.672
300	549.657	1.832	0.251	0.679
500	798.281	1.597	0.648	0.711
750	1133.314	1.511	0.879	0.762
1000	1496.158	1.496	1.022	0.818
1500	2305.750	1.537	1.221	0.931
2000	3226.464	1.613	1.376	1.045

---

[*] Holding other ouptuts at their sample menas

[**] Specific average costs is defined as total costs divided by ton-miles.

[†] Sample mean

Table 6.13 Average and Marginal Costs for Output 3
(y_3 = LTL > 500 miles)

Ton-Miles (millions)	Total Costs* ($ millions)	Specific Average Costs** ($/ton-mile)	Average Incremental Costs ($/ton-mile)	Marginal Costs ($/ton-mile)
5	121.007	24.201	-5.243	5.003
10	129.849	12.985	-1.737	2.986
20	143.908	7.195	-0.166	1.822
30	155.131	5.171	0.264	1.380
40	164.719	4.118	0.437	1.139
50	173.225	3.465	0.520	0.984
100	206.918	2.069	0.597	0.636
150	233.048	1.554	0.572	0.499
200	255.269	1.276	0.540	0.422
227.639†	266.430	1.170	0.397	0.392
500	354.053	0.708	0.414	0.256
750	416.631	0.556	0.359	0.208
1000	470.772	0.471	0.324	0.181
1500	564.536	0.376	0.278	0.150
2000	646.498	0.323	0.250	0.132
3000	790.035	0.263	0.214	0.111
3500	855.088	0.244	0.202	0.104

---

*Holding other outputs at their sample means

**Specific average costs is defined as total costs divided by ton-miles.

†Sample mean

Table 6.14 Average and Marginal Costs for Output 4

(y_4 = TL)

Ton-Miles (millions)	Total Costs* ($ millions)	Specific Average Costs** ($/ton-mile)	Average Incremental Costs ($/ton-mile)	Marginal Costs ($/ton-mile)
20	621.187	31.059	12.848	-9.095
30	421.526	14.051	1.910	-2.594
40	337.647	8.441	-0.665	-0.910
50	293.045	5.861	-1.424	-0.283
100	223.586	2.236	-1.407	0.306
150	214.962	1.433	-0.995	0.351
200	220.475	1.102	-0.719	0.355
300	246.289	0.821	-0.393	0.353
360.158†	266.430	0.740	-0.196	0.354
750	437.044	0.583	0.097	0.393
1000	573.962	0.574	0.210	0.431
2000	1327.028	0.664	0.481	0.621
35000	3148.002	0.899	0.795	0.977
4000	3965.360	0.991	0.900	1.112

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*Holding other outputs at their sample means

**Specific average costs is defined as total costs divded by ton-miles

†Sample mean

Table 6.15 Product-Specific Scale Economies at Sample Means

	OUTPUT			
	y_1 (= LTL < 250)	y_2 (= LTL 250-500)	y_3 (= LTL > 250)	y_4 (= TL)
Average Incremental Costs ($/ton-mile)	4.237	-4.159	0.397	-0.196
Marginal Costs ($/ton-mile)	1.746	0.536	0.392	0.354
Product-Specific Scale Economies	2.426	-7.759	1.013	-0.554

Short-haul LTL service is estimated to have the highest marginal cost (1.746 dollars/ton-mile), while TL traffic is estimated to have the lowest marginal cost (0.354 dollars/ton-mile). This latter figure is arpproximately 10 percent lower than that for long-haul LTL traffic.

From Table 6.15 we also see that product-specific scale economies exist only for y_1 — LTL movements with length of haul < 250 miles. Thus the mean firm would have incentive to expand its short-haul LTL business for a given rate level. however, that we are studying the technology of interregional/transcontinental carriers. The typical "short-haul"traffic in our sample represents movements of 150-250 miles. Interregional carriers are not involved in very short, local shipments (< 150 miles); these are handled by local, regional carriers. Thus our findings do not imply that large, interregional carriers would encroach upon the market for these local, regional carriers in a deregulated environment. Friedlaender, Spady and Wang Chiang (1981) classified general-freight carriers into three groups by length of haul: short-haul regional carriers (average length of haul of 120 miles), intermediate-haul regional carriers (average length of haul of 186 miles), and inter-regional carriers (average length of haul of 564 miles). Thus our findings suggest that in a deregulated environment interregional carriers could encroach upon the markets currently served by intermediate-haul, regional carriers. These markets have length of haul typically around 150-250 miles, which is the same as our y_1. Therefore, in the absence of regulatory constraints, the LTL market could well be divided into two types of carriers—regional carriers which handle very short, local shipments, and interregional carriers which handle other LTL shipments. The current intermediate-haul regional carriers could have difficulty remaining in this market because of their inability to compete with interregional carriers who are likely to have cost advantages due to economies of network configuration and network operation. Also, shippers are more likely to choose carriers with large network coverage. Thus the economies associated with short-haul traffic in conjunction with shipper preferences for dealing with a single carrier do much to help explain the recent movement toward mergers.

E. Economies of Scope

Economies of scope measure whether there are cost savings associated with the simultaneous production of many products. In the four-output case economies of scope exist with respect to the production of outputs y_1, y_2, y_3, and y_4 if

$$C(y_1,y_2,y_3,y_4) < C(y_1,0,0,0) + C(0,y_2,0,0) + C(0,0,y_3,0) + C(0,0,0,y_4) \tag{6.18}$$

and the degree of economies of scope, SC, is measured as

$$SC = \frac{C(y_1,0,0,0) + C(0,y_2,0,0) + C(0,0,y_3,0) + C(0,0,0,y_4) - C(y_1,y_2,y_3,y_4)}{C(y_1,y_2,y_3,y_4)} \tag{6.18a}$$

For the "typical" trucking firm operating at the sample mean, the cost of producing y_1, y_2, y_3, y_4 simultaneously is smaller than the cost of producing y_1, y_2, y_3, y_4 separately, with the degree of economies of scope SC equal to 1.576 at the sample mean. Thus the existence of economies of scope encourages carriers to produce more than one output.

Since the firms in our sample produce relatively little short-haul output and appear to have some product-specific scale economies associated with their output, it is interesting to ask whether economies of scope are associated with the production of short-haul LTL traffic. Thus, suppose firms were to specialize and only produce y_1 on the one hand and combinations of y_2, y_3 and y_4 on the other. Would the sum of the costs of joint production? This can be answered by estimating the product-specific scope economies associated with y_1. Formally, this is written as:

$$SC_1 = \frac{C(y_1,0,0,0) + C(0,y_2,y_3,y_4) - C(y_1,y_2,y_3,y_4)}{C(y_1,y_2,y_3,y_4)} \tag{6.19}$$

where SC_1 deontes the economies of scope for y_1. Thus cost advantages accrue to firms producing y_1 jointly with other products if $SC_1 > 0$.

Table 6.16 gives the estimated product-specific economies of scope for the "typical" firm at the sample mean. These are all positive, implying that there are cost advantages to producing outputs simultaneously. This results largely from the existence of common fixed costs. It is interesting to note that economies of scope are especially high for y_2. This suggests that it would be extremely advantageous to produce intermediate-haul LTL service jointly with other services. The policy implication of this finding is that the LTL market, which is currently shared by intermediate-haul regional carriers and interregional carriers, would face increasing competition in the absence of regulation. Interregional carriers appear to have considerable incentives to encroach upon this market to compete with intermediate-haul regional carriers.

Recall that economies of scope plus declining average incremental costs are also sufficient conditions to guarantee subadditivity. While this analysis indicates the existence of scope economies, the previous analysis showed little evidence of declining average incremental costs. Thus we again reject the hypothesis of natural monopoly in the regulated market for common carriers of general commodities.

Table 6.16 Degrees of Scope Economies at Sample Means

Output	Degree of Scope Economies
y_1 (LTL < 250 miles)	0.432
y_2 (LTL 250 - 500 miles)	1.313
y_3 (LTL > 500 miles)	0.467
y_4 (TL)	0.747

IV. A Simulation Analysis

The previous analysis focused on the behavior of the "typical" carrier operating around the sample mean. Since, however, the firms in our sample show wide variability in size,[15] it is useful to analyze the cost behavior of firms representing the extremes of the sample. To do this, we performed a simulation analysis, which is described in this section.

The merger movement currently underway in the U.S. trucking industry involves many interregional carriers. An interesting policy question is to what extent these mergers can be justified on a purely cost basis: Are there some interregional carriers who can gain economies from expanding their operating authorities as well as their level of output? We have already studied the costs of the typical firms at sample means and found that these mean firms enjoy economies of scope

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[15] The smallest firm has an output of 20.6 million ton-miles while the largest firm has an output of 5183 million ton-miles.

but not economies of scale. We now investigate carriers at either end of the spectrum away from the sample mean firm. We take the 20 largest and the 20 smallest carriers from our sample,[16] and estimate costs for these two groups at their respective sample means. The results are shown in Tables 6.17 and 6.18.

A comparison of these two tables indicates that the shapes of average and marginal costs are generally the same over the entire sample, but that the magnitudes of these cost vary by size of firm. For example, both specific average costs and average incremental costs decline for output 1 and increase for output 2 much more dramatically among giant carriers than among small carriers or for the sample as a whole. Thus these giant carriers seem to face a different cost structure, which could result from inherent differences in technology. On the other hand, these cost differences may be partially due to errors in estimating since a flexible function will magnify whatever predictive bias may exist as the point of evaluation diverges from the point of approximation. For instance, as stated earlier, the marginal cost of y_1 seems to be upwardly biased, resulting in a very high estimate for giant carriers (8.259 dollars/ton-mile at the sample mean).

Using Eq. (4.6), we calculate the multiproduct returns to scale for giant carriers at the sample mean to be 0.9293. Thus these carriers exhibit slightly decreasing returns to scale. Hence there is no evidence that the giant interregional carriers enjoy economies of scale. The multiproduct returns to scale for small firms is estimated to be 1.3188, indicating that smaller interregional carriers seem to have incentive to expand their output, at least proportionally.

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[16] See Appendixes B and C. The 20 largest firms are referred to as "giant" carriers.

Table 6.17 Average and Marginal Costs for 20 Largest Firms, by Output

OUTPUT y_1 (LTL < 250 miles)

Ton-Miles (millions)	Total Costs ($ millions)	Specific Average Costs** ($/ton-mile)	Average Incremental Costs ($/ton-mile)	Marginal Costs ($/ton-mile)
5	725.622	145.124	42.955	8.413
5.067†	726.484	143.375	21.564	8.259
20	778.829	38.941	13.399	0.756
30	779.206	25.974	8.945	0.211
40	775.161	19.379	6.608	0.002
50	769.593	15.392	5.175	-0.094
100	739.372	7.394	2.285	-0.188
150	713.351	4.756	1.350	-0.174
200	691.598	3.458	0.904	-0.154
300	656.904	2.190	0.487	-0.122
OUTPUT y_2 (LTL 250-500 miles)				
10	995.711	99.571	-39.338	-22.017
20	791.390	39.570	-29.885	-4.745
30	738.396	24.613	-21.690	-1.495
40	723.729	18.093	-16.634	-0.339
50	724.511	14.490	-13.292	0.201
53.0437†	726.484	13.696	-6.626	0.308
150	900.378	6.003	-3.258	1.046
200	1010.245	5.051	-1.894	1.092
300	1237.999	4.127	-0.504	1.137
500	1712.519	3.425	0.647	1.199
750	2339.068	3.119	1.267	1.276
1000	3004.414	3.004	1.615	1.356
1500	4454.590	2.970	2.044	1.516
2000	6064.736	3.032	2.338	1.675

(continued)

Table 6.17, continued

OUTPUT y_3 (LTL > 500 miles)

Ton-Miles (millions)	Total[*] Costs ($ millions)	Specific Average Costs[**] ($/ton-mile)	Average Incremental Costs ($/ton-mile)	Marginal Costs ($/ton-mile)
10	107.818	10.782	-12.406	3.738
20	132.034	6.602	-4.992	2.443
30	150.889	5.030	-2.700	1.929
40	166.993	4.175	-1.622	1.642
50	181.351	3.627	-1.011	1.454
100	239.363	2.394	0.075	1.015
150	285.801	1.905	0.359	0.834
200	326.294	1.631	0.472	0.730
300	397.022	1.323	0.550	0.610
750	644.212	0.859	0.550	0.422
927.3794[†]	726.484	0.783	0.495	0.391
2000	1151.299	0.576	0.460	0.302
3000	1491.511	0.497	0.420	0.268
3500	1650.562	0.472	0.405	0.256

OUTPUT y_4 (TL)

Ton-Miles (millions)	Total[*] Costs ($ millions)	Specific Average Costs[**] ($/ton-mile)	Average Incremental Costs ($/ton-mile)	Marginal Costs ($/ton-mile)
30	1227.111	40.904	25.020	-17.600
40	915.852	22.896	10.984	-8.094
50	752.466	15.049	5.519	-4.423
100	484.212	4.842	0.077	-0.327
150	421.394	2.809	-0.367	-0.002
200	402.708	2.014	-0.369	0.153
300	407.203	1.357	-0.231	0.250
750	576.924	0.769	0.134	0.330
1000	705.961	0.706	0.229	0.357
1037.0299[†]	726.484	0.701	0.167	0.361
2000	1376.627	0.688	0.450	0.476
3000	2291.504	0.764	0.605	0.610
3500	2846.152	0.813	0.677	0.683
4000	3469.424	0.867	0.748	0.760

Table 6.18 Average and Marginal Costs for 20 Smallest Firms, by Output

OUTPUT y_1 (LTL < 250 miles)

Ton-Miles (millions)	Total Costs* ($ millions)	Specific Average Costs** ($/ton-mile)	Average Incremental Costs ($/ton-mile)	Marginal Costs ($/ton-mile)
5	126.917	25.383	9.095	8.707
10	162.368	16.237	8.093	5.257
16.72547†	191.593	11.455	5.508	3.545
30	227.130	7.571	4.856	2.220
40	245.261	6.132	4.096	1.749
50	259.491	5.190	3.561	1.448
100	303.762	3.038	2.223	0.789
150	328.980	2.193	1.650	0.545
200	346.205	1.731	1.324	0.416
300	369.128	1.230	0.959	0.282

OUTPUT y_2 (LTL 250-500 miles)

Ton-Miles (millions)	Total Costs* ($ millions)	Specific Average Costs** ($/ton-mile)	Average Incremental Costs ($/ton-mile)	Marginal Costs ($/ton-mile)
5	234.378	46.876	-30.080	-1.504
10	197.977	19.798	-18.680	1.368
18.2496†	191.593	10.499	-9.659	1.648
30	201.950	6.732	-6.094	1.545
50	229.819	4.596	-3.099	1.398
100	309.371	3.094	-0.754	1.254
150	392.861	2.619	0.054	1.217
200	479.183	2.396	0.472	1.213
300	660.543	2.202	0.919	1.246
500	1059.749	2.119	1.350	1.357
750	1628.234	2.171	1.658	1.519
1000	2273.496	2.273	1.889	1.686
1500	3791.828	2.528	2.271	2.024
2000	5611.943	2.806	2.614	2.364

(continued)

Table 6.18, continued

OUTPUT y_3 (LTL > 500 miles)

Ton-Miles (millions)	Total Costs* ($ millions)	Specific Average Costs** ($/ton-mile)	Average Incremental Costs ($/ton-mile)	Marginal Costs ($/ton-mile)
5	189.243	37.849	-3.815	5.877
8.5916†	191.593	22.300	-1.673	3.868
20	203.156	10.158	-0.258	2.050
30	212.539	7.085	0.141	1.526
40	220.932	5.523	0.315	1.243
50	228.542	4.571	0.404	1.063
100	259.370	2.594	0.511	0.664
150	283.506	1.890	0.501	0.509
200	304.010	1.520	0.478	0.424
300	338.633	1.129	0.434	0.330
500	394.065	0.788	0.371	0.244
750	450.034	0.600	0.322	0.194
1000	497.825	0.498	0.290	0.166
1500	579.366	0.386	0.247	0.134
2000	649.532	0.325	0.221	0.116
3000	770.326	0.257	0.187	0.095
3500	824.318	0.236	0.176	0.088
OUTPUT y_4 (TL)				
10	631.290	63.129	-104.048	-13.750
20	317.944	15.897	-67.691	-0.521
30	239.744	7.991	-47.734	0.603
40	206.956	5.174	-36.620	0.788
48.99535†	191.593	3.910	-29.604	0.807
100	173.921	1.739	-14.978	0.690
150	185.808	1.239	-9.906	0.626
200	205.379	1.027	-7.332	0.598
300	254.939	0.850	-4.7[illegible]	0.587

Table 6.18, continued

(OUTPUT y_4, continued)

Ton-Miles (millions)	Total Costs[*] ($ millions)	Specific Average Costs[**] ($/ton-mile)	Average Incremental Costs ($/ton-mile)	Marginal Costs ($/ton-mile)
500	379.296	0.759	-2.585	0.627
750	574.125	0.766	-1.464	0.716
1000	812.564	0.813	-0.859	0.822
1500	1429.072	0.953	-0.162	1.067
2000	2249.793	1.125	0.289	1.346
3000	4597.345	1.532	0.975	2.000
3500	6173.105	1.764	1.286	2.374
4000	8050.689	2.013	1.595	2.781

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[*] Holding other outputs at their sample means

[**] Specific average costs is defined as total costs divided by ton-miles.

[+] Sample mean

Next, we investigate the existence of scale economies with respect to each output. The product-specific scale economies, as shown in Table 6.19, suggest that the giant interregional carriers have incentive to expand their y_1 and y_3 outputs, while small interregional carriers have incentive to expand only their y_1 output. Thus the overall economies of scale for small interregional carriers could in fact be a reflection of the existence of economies of scope. As we indicated in Chapter Four, economies of scope could magnify the degree of overall scale economies. There is still the possibility of overall increasing returns to scale, even if product-specific returns to scale are constant or decreasing. This could be the case for the small interregional carriers. To investigate this issue further, we undertake a cross sectional analysis of carrier costs.

Table 6.20 gives the estimated Hessian matrices for the 20 largest and smallest carriers evaluated at their sample means. Again, the matrices are not positive—definite. Cost complements exist between some product pairs but not all of them. In addition, tests for transray convexity performed for each product pair as suggested in Chapter Six, Section III.D failed to indicate that the cost surface is transray convex.

We then examine the existence of economies of scope among these giant and small carriers at their sample means (see Table 6.21). Both groups of carriers are shown to obtain cost advantages from producing various types of outputs jointly. However, the tendency toward cost advantages is much higher for the smaller carriers. With respect to output type, we find that small carriers exhibit product-specific

Table 6.19. Product-Specific Scale Economies for the 20 Largest and 20 Smallest Carriers at Sample Means

	Output			
	y_1 (= LTL < 250)	y_2 (= LTL 250-500)	y_3 (= LTL > 500)	y_4 (= TL)
20 Largest Carriers				
Average Incremental Costs ($/ton-mile)	21.564	-6.626	0.495	0.167
Marginal Costs ($/ton-mile)	8.259	0.308	0.391	0.361
Product-Specific Scale Economies	2.611	-21.513	1.266	0.463
20 Smallest Carriers				
Average Incremental Costs ($/ton-mile)	5.508	-9.659	-1.673	-14.978
Marginal Costs ($/ton-mile)	3.545	1.648	3.868	0.690
Product-Specific Scale Economics	1.554	-5.861	-4.325	-21.707

Table 6.20 Hessian Matrices for the 20 Largest and 20 Smallest Carriers at their Sample Means

	Output*			
	y_1 (LTL < 250 miles)	y_2 (LTL 250-500 miles)	y_3 (LTL > 500 miles)	y_4 (TL)
20 Largest Carriers				
y_1	-2.323277	-0.126482	-0.009313	0.015882
y_2	-0.126482	0.032021	0.000603	-0.001823
y_3	-0.009313	0.000603	-0.000183	0.000202
y_4	0.015882	-0.001823	0.000202	0.000012
20 Smallest Carriers				
y_1	-0.165406	0.000296	-0.047067	0.034849
y_2	0.000296	0.007876	0.069419	-0.025114
y_3	-0.047067	0.069419	-0.284943	0.020802
y_4	0.034849	-0.025114	0.020802	0.008232

*Unit: 10^{-6}

Table 6.21 Degree of Scope Economies for the 20 Largest and 20 Smallest Carriers at Sample Means

Output	Degree of Scope Economies
Largest Carriers	
y_1	-0.074
y_2	1.064
y_3	-0.195
y_4	-0.101
Smallest Carriers	
y_1	10.053
y_2	5.174
y_3	4.190
y_4	8.251

economies of scope for each type of output, while the giant, nationwide interregional carriers exhibit these economies for output y_2 only. Thus giant carriers with annual ton-miles over 1 billion have virtually exhausted their economies of scope. There do not seem to be particular cost advantages from producing one type of output jointly with another output type. The economies of scope with respect to output y_2, exhibited by all carrier size groups, suggest that trucking operations within this range involve less specialized equipment and technology than firms dealing with the other output types. Firms with facilities and technologies devoted to short- or long-haul LTL operations, or to TL operations, have the potential to produce intermediate-haul LTL service more cheaply than firms whose facilities and technology are devoted exclusively to intermediate-haul LTL operations. This is supported by the evidence of weak cost complementarities between y_2 and the other outputs, as indicated by the Hessian matrix. Thus the C_{2j} coefficients are estimated to be negative for giant carriers and carriers at grand sample means, except for C_{23}. The positive sign on C_{23} is somewhat plausible since it implies that these giant carriers may have exhausted their economies of scope.

The evidence of no economies of scope and of slightly decreasing returns to scale for the giant nationwide interregional carriers suggests that these firms have reached their optimal size and geographical coverage. The evidence of strong economies of scope for the smaller carriers helps explain the current merger movement among these firms who are attempting to extend their operating authorities.

CHAPTER SEVEN

CONCLUSIONS

This study has examined the technology of interregional and transcontinental common carriers of general commodities using a more elaborate and realistic approach than has been attempted previously. For the first time, heterogeneous trucking outputs are considered as multiple products and are explicitly entered as arguments into the cost function. The impact of network configuration and network operations upon carriers' costs has also been included in the general cost functions through global network variables. The empirical results show that the use of network variables and output disaggregation substantially improve the empirical analysis.

Previous studies of the costs of these large, interregional carriers suggested that they face slightly increasing returns to scale. Our study indicates that there is no evidence of scale economies. However, these interregional carriers do exhibit economies of scope (i.e., there are cost advantages to joint production), which helps explain the increasing concentration ratios among these carriers as documented by the Senate Judiciary Committee (1980). The recent increase in mergers and acquisitions, as well as internal growth, in this sector of the trucking industry are in fact due to the existence of economies of scope rather than economies of scale.

Before summarizing the policy implications of these new empirical findings, let us briefly summarize the assumptions and procedures that were used to arrive at these results. First, we observe that regulatory constaints limit carriers' flexibility to adjust rates and require common-commodity carriers to haul freight at rates established by the ICC. Therefore, we study the technology of these carriers by means of cost functions rather than profit functions. In modeling a cost function for the trucking industry, a major issue is the appropriate definition of output, since trucking output is extremely heterogeneous. The ideal case would be to treat each type of service between an origin-destination pair as an individual output, but this is infeasible in the real world. Therefore, we use the two most critical factors, length of haul and type of service (TL or LTL) to classify trucking movements into four types of traffic:

y_1 - LTL ton-miles with length of haul under 250 miles, referred to as short-haul LTL traffic

y_2 - LTL ton-miles with length of haul of 250-500 miles, referred to as intermediate-haul LTL traffic

y_3 - LTL ton-miles with length of haul over 500 miles, referred to as long-haul LTL traffic

y_4 - TL ton-miles.

Since location-specific output definitions are not feasible, it is useful to have global network measures in the cost function to reflect further the impacts of network upon costs. We constructed four variables of this type — one to measure whether a network is fully connected, one to measure the operating density of a given network configuration, one to measure the ability to provide direct routing service, and the last to measure the average amount of traffic handled by a terminal. With the help of these network variables, we can examine the existence of economies of network configuration and economies of network operation. These two economies are not due to the quantity of output. Rather, they result from the spatial arrangement of a network and the strategies of routing traffic over the network.

Our estimation results again indicate that trucking production is nonhomothetic — a conclusion shared by previous studies.[1] Thus any attempt to model trucking technology by a homothetic function such as the Cobb-Douglas function will lead to biased results. Since the technology is nonhomothetic, it is not possible to make global generalizations concerning returns to scale and network effects upon costs. These depend upon the level of factor prices, outputs, and network characteristics, etc. Thus we first examine the technology of a hypothetical carrier whose factor prices, network variables and levels of output are assumed to be at the sample mean. This gives us the cost behavior of a typical firm in the sample and the results are generally statistically reliable, since our translog cost function is also approximated at the sample mean. We then investigate scale economies, network effects upon costs, etc., for firms whose factor prices and network variables diverge from mean values.

For policy purposes, our ultimate concern is to what extent the large, interregional carriers would behave as natural monopolists. A natural monopoly requires ray subadditivity as well as cross sectional subadditivity. Subadditivity along a ray means that a single firm can produce a given amount at a lower cost than many firms if products are produced at fixed proportions. Traditional multiproduct economies of scale are one of the sufficient conditions for the existence of ray subadditivity.

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[1] See, for example, Friedlaender and Spady (1981), Wang Chiang (1979).

Cross sectional subadditivity is concerned with the existence of cost advantages associated with a single firm producing an output bundle relative to many firms, each producing a subset of that bundle at the same level. A sufficient condition for this is transray convexity. At the sample mean, our tests reject the hypotheses that there exist multiproduct economies of scale, and that the cost function is transray convex. Therefore, the empirical evidence does not indicate that this sector of the trucking industry would behave as a natural monopoly in a deregulated environment.

This leads to the question of what economic motivation lies behind the current merger movement in this industry. We thus look more closely into the technology by examining cost complimentarities between outputs, product-specific scale economies, as well as incremental costs, etc. We find that although there are no economies of scale in output quantity, there are economies of scope associated with joint production. These economies of scope arise from economies of network configuration and economies of network operation, as well as shared inputs. The empirical evidence of this study indicates that 1) there are cost advantages associated with a high degree of network connectivity which brings about efficiencies through direct routing strategies; and 2) these cost advantages increase with firm size since larger firms are better able to provide direct service. The existence of economies of network configuration thus explain why large carriers enjoy natural advantages over their smaller counterparts: large carriers can utilize their own fleets, while smaller carriers must interline with other firms in order to offer servic at the same national level.

Furthermore, conditional on network configuration, there are economi of network operation. Given a network configuration, cost advantages could result from better routing and terminal consolidation practices; in other words, there are returns to traffic density. Our empirical study supports this proposition. Increases in traffic density as measured by (1 - Chi index) reduce the demand for every factor, which results in savings in total costs. Both economies of network configuration and economies of network operation justify the current merger and acquisition movement on a cost basis.

The above findings also hold for firms away from the sample mean. Our simulation study indicates that the largest firms in our sample face slightly decreasing returns to scale. Although they also enjoy economies of scope, these economies are very slight. Carriers with annual ton-miles of over 1 billion have virtually exhausted their scope economies. The findings of weak economies of scope and decreasing returns to scale for these giant, transcontinental carriers suggest that these firms have reached their optimal size. Thus there would be no advantages to these firms to increase their size of output or geographical coverage. Smaller interregional carriers on the other hand exhibit very strong economies of scope. Thus these firms have incentive not only to jointly produce all outputs — short-, intermediate- and long-haul LTL as well as TL services — but also to expand the level of these outputs. This explains why these carriers are heavily involved in the current merger movement in the trucking industry.

Before examining the policy implications of these findings it is useful to clarify the terminology by dividing the LTL trucking market into 5 segments by length of haul:

short-haul <u>regional</u> markets with typical length of haul of less than 150 miles

intermediate-haul <u>regional</u> markets with typical length of haul of less than 200 miles

short-haul <u>interregional</u> markets with typical length of haul of 150-250 miles

intermediate-haul <u>interregional</u> markets with typical length of haul of 250-500 miles

long-haul <u>interregional</u> markets with typical length of haul of over 500 miles

Notice that the last three categories are interregional markets while the first two are regional markets. Thus general-freight carriers can also be classified according to the markets in which they operate. For example, a carrier operating mainly in the long-haul interregional market can be classified as a long-haul interregional carrier. A carrier is usually not limited to only one type of market. For instance, a short-haul interregional carrier serves mainly short-haul interregional markets, but usually also serves intermediate- or possible long-haul interregional markets. In the absence of regulatory constraints, a short-haul interregional carrier could also provide service to the markets which are currently dominated by intermediate-haul regional carriers.

Our previous studies[2] have suggested that the technology of short-haul regional carriers is quite specialized. It is not likely that

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[2] See Friedlaender and Spady (1981), Friedlaender, Spady and Wang Chiang (1981).

other types of carriers — especially interregional carriers — would compete in this market. These short-haul regional carriers currently face slightly decreasing returns to scale. We continue to believe, as indicated by our previous studies, that this sector of the trucking industry would be competitively organized in a deregulated environment. The number of carriers operating in each of these short-haul regional markest would depend on the level of demand in each market.

The operations of long-haul interregional carriers require a large network with a considerable number of terminals in order to be able to perform extensive vehicle routings and terminal consolidations to achieve lower costs. The existing giant, nationwide interregional carriers would still dominate this market. Since these carriers are estimated to exhibit decreasing returns to scale, there would be no incentive for them to expand further in size. However, because of the existence of economies of scope, they would still have incentive to expand their authority rights to take advantage of economies of network configuration and of network operation. Thus in the absence of regulation these carriers would become involved in other markets — short- and intermediate-haul interregional markets as well as TL markets. However, since the scope economies have almost been exhausted by these carriers, we would expect to see their spatial expansion saturated very quickly. Furthermore, in the absence of regulation, we would not expect to see any dramatic change among these carriers. They would still provide service mainly to the long-haul LTL and TL markets, with a considerable amount of short- and intermediate-haul interregional operations as byproducts resulting from the nature of network operations. They would compete among themselves with a certain degree of inherent monopoly power due to the spatial location of networks.

It is less clear how the other sectors of the trucking industry would behave in the absence of regulation. Naturally, without regulatory constraints on operating rights, regional and interregional carriers would become more competitive. The terms "regional" and "interregional" would be irrelevant and only length of haul would be an important measure. The markets currently dominated by intermediate-haul regional carriers would face competition from interregional carriers. Similarly, short-haul and possibly some intermediate-haul interregional markets would be shared by existing regional carriers. Because of the existence of economies of network configuration and of network operation, we would expect larger carriers (currently regional or interregional) to have cost advantages over smaller carriers. Therefore, we would predict that these carriers would expand their networks geographically through mergers and acquisitions as well as through internal growth. Furthermore, in the absence of regulation, large carriers could use rate deductions to push small carriers out of markets since large carriers are better able to cross-subsidize among markets. Thus the number of carriers handling intermediate-haul LTL traffic would be considerably reduced. After the markets stablize, a new competitive environment would result. Under the new market equilibrium, the number of carriers operating at each origin-destination market would depend on the level of demand in that market. Again, carriers providing service for this sector of the trucking industry would gain a certain degree of monopoly power due simply to the existence of economies of spatial scope. Nevertheless, the extent of this monopoly power is sufficiently small that workable competition would prevail in these markets.

In conclusion, the most important finding of this research for policy purposes is that general-freight common-commodity carriers have no perceptible tendency to behave as natural monopolists in a deregulated environment. Thus although the number of carriers in certain markets would probably fall and the tendency toward mergers should increase, the efficient size of firms appears to be sufficiently small that monopolization would not exist. Competition, while perhaps not perfect, would surely be workable.

APPENDIX A

105 Common Carriers of General Commodities

No.	Region * Code	
1	08	Garrett Freight Lines Inc.
2	09	Pacific Intermountain Express Co.
3	04	Dean Truck Line Inc.
4	02	Preston Trucking Co. Inc.
5	02	B & P Motor Express Inc.
6	03	Roadway Express Inc.
7	07	Red Arrow Freight Lines Inc.
8	07	Red Ball Motor Freight Inc.
9	03	The O-K Trucking Co.
10	04	Carolina Freight Carriers Corp.
11	04	Ryder Truck lines Inc. (Fla. Corp.)
12	03	A & M Truck Line Inc.
13	01	Quinn Freight Lines Inc.
14	02	Jones Motor (Allegheny Corp.)
15	06	Mid-American Lines Inc.
16	05	Werner Continental Inc.
17	03	Western Gillette, Inc.
18	06	Churchill Truck Lines Inc.
19	03	Transamerican Freight Line Inc.
20	02	Branch Motor Express Co.
21	04	Gordons Transports Inc.
22	03	Wilson Freight Co.
23	03	Duff Truck Line Inc. (OH)
24	04	Terminal Transport Co. Inc.
25	03	Great Lakes Express Co.
26	05	All-American Inc.
27	05	Briggs Transportation Co. (Minn. Corp.)
28	02	Burgmeyer Bros. Inc.
29	07	Arkansas-Best Freight System Inc.
30	01	Holmes Transportation Inc.
31	01	Hemingway Transport Inc.

(Common Carriers of General Commodities--continued)

No.	Region Code *	
32	07	Southern Pacific Transp. Co. (of Texas & Louisi.)
33	03	Tucker Freight Lines Inc.
34	06	The *Santa Fe Trail Trans. Co.
35	04	McLean Trucking Company
36	02	Hermann Forwarding Co.
37	08	IML Freight Inc.
38	07	TIME - DC Inc.
39	03	Cooper-Jarrett Inc.
40	03	Interstate Motor Freight Sys.
41	04	Central Truck Lines Inc.
42	07	East Texas Motor Freight Lines Inc.
43	04	Howard * Hall Co. Inc.
44	09	Consolidated Freightways Corp. of Del.
45	09	Wells Cargo Inc.
46	03	Dohrn Transfer Co.
47	03	Suburban Motor Freight Inc.
48	07	Brown Express Inc.
49	08	Illinois-California Express Inc.
50	04	ET & WNC Transportation Co.
51	06	Graves Truck Line Inc.
52	09	Delta Lines Inc.
53	04	Brown Transport Corp.
54	03	Renner's Express Inc.
55	04	Georgia Highway Express Inc.
56	02	Eazor Express, Inc.
57	02	Red Star Express Lines
58	04	The * Mason & Dixon Lines, Inc.
59	07	Strickland Transp. Co. Inc.
60	08	Salt Creek Freightways
61	02	Motor Freight Express Inc.
62	04	Pilot Freight Carriers Inc.

(Common Carriers of General Commodities--continued)

No.	Region Code *	
63	07	Lee Way Motor Freight Inc. (Del. Corp.)
64	02	Mushroom Transportation Co. Inc.
65	02	Hall's Motor Transit Co.
66	03	Spector Freight System Inc.
67	03	Associated Truck Lines Inc.
68	02	New Penn Motor Express Inc.
69	09	O N C Freight Systems
70	04	Akers Motor Lines Inc.
71	06	Campbell Sixty-Six Express Inc.
72	08	Navajo Freight Lines Inc.
73	05	Admiral-Merchants Motor Freight Inc.
74	02	Oneida Motor Freight Inc.
75	02	Dorn's Transportation Inc. (N.Y. Corp.)
76	04	Bowman Transportation Inc.
77	04	Estes Express Lines
78	05	Barber Transportation Co.
79	09	System 99
80	04	Thurston Motor Lines Inc.
81	04	Johnson Motor Lines Inc.
82	04	Old Dominion Freight Line
83	05	Advance-United Expressways Inc. (Minn. Corp.)
84	03	Transport Motor Express inc. (Del. Corp.)
85	02	Maislin Transport Ltd.
86	01	St. Johnsburg Trucking Co. (Vt.)
87	01	Schuster Express Inc.
88	05	Clairmont Transfer Co.
89	05	Murphy Motor Freight Lines Inc. (Minn. Corp.)
90	04	Overnite Transp. Co.
91	05	Chippewa Motor Freight Inc.
92	02	Lyons Transp. Lines Inc.
93	02	Boss Linco Lines Inc.
94	04	Tennessee Carolina Transp. Inc. (Tenn. Corp.)

(Common Carriers of General Commodities--continued)

No.	Region Code*	
95	09	Transcon Lines
96	02	Smith's Transfer Corp.
97	07	Jones Truck Lines Inc.
98	05	Twin City Freight Inc.
99	05	C W Transport Inc.
100	06	Middlewest Freightways Inc.
101	04	Southeastern Freight Lines Inc.
102	03	Yellow Freight System Inc.
103	04	Mercury Motor Express Inc.
104	07	Texas-Oklahoma Express Inc.
105	06	Crouse Cartage Company

*Region Codes:

01	New England
02	Middle Atlantic
03	Central
04	Southern
05	North Western
06	Mid Western
07	South Western
08	Rocky Mountain
09	Pacific

APPENDIX B

20 Smallest Common Carriers of General Commodities

Ton-miles	Firm Names
20,566,654	Dean Truck Line Inc.
25,971,182	Twin City Freight Inc.
26,157,733	Hermann Forwarding Co.
64,320,791	Advance-United Expressways Inc. (Minn. Corp.)
63,618,837	Barber Transportation Co.
68,581,457	Renner's Express Inc.
74,157,047	Crouse Cartage Company
81,404,854	New Penn Motor Express Inc.
89,604,160	Dorn's Transportation Inc. (N.Y. Corp.)
90,749,149	Salt Greek Freightways
96,501,359	Estes Express Lines
96,919,758	Middlewest Freightways Inc.
97,151,741	Holmes Transportation Inc.
97,594,855	Southeaster Freight Lines Inc.
99,471,231	Georgia Highway Express Inc.
102,051,140	Schuster Express Inc.
102,603,865	Lyons Transp. Lines Inc.
107,944,862	Wells Cargo Inc.
110,736,447	Central Truck Lines Inc.
124,054,427	Duff Truck Line Inc. (OH)

APPENDIX C

20 Largest Common Carriers of General Commodities

Ton-miles	Firm Names
5,183,234,608	Consolidated Freightways Corp. of DEL
5,100,809,088	Yellow Freight System Inc.
4,740,432,256	Roadway Express Inc.
2,998,016,192	McLean Trucking Company
2,651,287,936	Ryder Truck Lines Inc. (Fla. Corp.)
2,303,090,080	Spector Freight System Inc.
2,241,959,328	Pacific Intermountain Express Co.
2,080,692,192	Transcon Lines
1,708,411,280	TIME--DC Inc.
1,587,223,376	Navajo Freight Lines Inc.
1,548,911,120	Lee Way Motor Freight Inc. (Del. Corp.)
1,464,391,120	East Texas Motor Freight Lines Inc.
1,431,750,896	Smith's Transfer Corp.
1,304,945,424	IML Freight Inc.
1,193,596,640	Interstate Motor Freight System
1,088,295,616	The * Mason & Dixon Lines, Inc.
1,086,319,872	Arkansas-Best Freight System Inc.
1,057,778,968	Carolina Freight Carriers Corp.
1,005,925,224	Terminal Transport Co. Inc.
949,409,960	Bowman Transportation Inc.

APPENDIX D

FIML Estimation Procedures

The FIML estimation procedures embodied in the translog estimation package written by Spady and Snow are based upon original subroutines in TSP which are developed using the estimation and inference methods presented in Berndt, Hall, Hall and Hausman (1974). These procedures are briefly described as follows.

Let us define the system of equations to be estimated as

$$F(Y, X\beta) = U$$

where: $Y = T \times M$ matrix of endogenous variables

$X = T \times K$ matrix of predetermined exogenous variables

$U = T \times M$ matrix of structural disturbances

$\beta = K \times M$ matrix of parameters to be estimated

M = number of equations in the system

T = number of observations

K = number of parameters

FIML does the following procedures to calculate the likelihood function and the gradient:

$$\ell n L(\beta) = \sum_{t=1}^{T} \ell n |J_t| - \frac{T}{2} \ell n |F'F|$$

$$\frac{\partial \ell n L(\beta)}{\partial \beta} = \sum_{t=1}^{T} \sum_{k=1}^{K} \sum_{m=1}^{M} (J_t) \frac{\partial J_{t,k,m}}{\partial \beta} - \frac{T}{2} \sum_{t=1}^{T} \frac{\partial F_t}{\partial \beta} \left(\sum_{t=1}^{T} F_t' F_t \right)^{-1} F_t'$$

where J is the Jacobian.

The Gauss gradient method is used to search for the maximum. The direction vector d in iteration is evaluated as $d = Qg$ where $g = \partial L/\partial \beta$ and $Q = R_T^{-1}$ and

$$R_T = \sum_{t=1}^{T} \left(\frac{\partial L_t}{\partial \beta}\right)\left(\frac{\partial L_t}{\partial \beta}\right)' \quad .$$

Convergence of the iterative process is achieved when

$$d_k \leq \varepsilon(|\beta_k| + 10\varepsilon) \qquad k = 1,\ldots,K$$

where ε is a prescribed tolerance which has been defined as 0.01 in the program.

References and Bibliography

Ayala-Oramas, U. (1975), "The Cost Structure of Regulated Trucking," Ph.D. dissertation, Massachusetts Institute of Technology, Department of Civil Engineering.

Buamol, W. J. (1977), "On the Proper Cost Tests for Natural Monopoly in a Multiproduct Industry," American Economic Review, 67, pp. 809-822.

Baumol, W. J., E. E. Bailey and R. D. Willig (1977), "Weak Invisible Hand Theorems on Pricing and Entry in a Multiproduct Natural Monopoly," American Economic Review, 67, pp. 350-365.

Baumol, W. J., and Y. M. Braunstein (1977), "Empirical Study of Scale Economies and Production Complementarity: The Case of Journal Publication," Journal of Political Economy, 85, No. 5.

Baumol, W. J., J. C. Panzar, and R. D. Willig (1979), Unpublished manuscript, Chapters 2, 3, 4, 7, and 16 (draft).

Berndt, E. R., B. H. Hall, R. E. Hall, and J. A. Hausman (1974), "Estimation and Inference in Nonlinear Structural Models," Annals of Social and Economic Measurement, 3, pp. 653-668.

Berndt, E. R., and D. O. Wood (1975), "Technology, Prices, and the Derived Demand for Energy," Review of Economics and Statistics, 57, pp. 259-268.

Berndt, E. R., and M. S. Khaled (1979), "Parametric Productivity Measurement and Choice among Flexible Functional Forms," Journal of Political Economy, 87, No. 6, pp. 1220-1246.

Boyer, K. D. (1981), "Equilizing Discrimination and Cartel Pricing in Transport Rate Regulation," Journal of Political Economy, 89, No. 2, pp. 270-28

Burgess, D. F. (1975), "Duality Theory and Pitfalls in the Specification of Technology," Journal of Econometrics, 3, pp. 105-121.

Caves, D. W., L. R. Christensen, and M. W. Tretheway (1978), "Flexible Cost Functions for Multiproduct Firms," Discussion Paper #7818, Social Systems Research Institute, University of Wisconsin, Madison.

Caves, D. W., and L. R. Christensen (1980), "Global Properties of Flexible Functional Forms," American Economic Review, 70, pp. 423-432.

Chow, G (1978), The Economics of the Motor Freight Industries, Indiana University, School of Business.

Christensen, L. R., D. W. Jorgenson and L. J. Lau (1971), "Conjugate Duality and the Transcendental Logarithmic Production Function," Econometrica, 39, pp. 255-256.

Daughety, A. F., and M. A. Turnquist (1979), "Development of Hybrid Cost Functions from Engineering and Statistical Techniques: The Case of Rail," Northwestern University, The Transportation Center.

de Neufville, R., and C. King (1977), "Information Needs and Performance Measures," U.S. Department of Transportation Report DOT-OS-50239.

Dicer, G. N. (1971), "Economies of Scale and Motor Carrier Optimum Size," Quarterly Review of Economics and Business, 11, pp. 28-37.

Diewert, W. E. (1974), "Applications of Duality Theory," in M. D. Intrilligator and D. A. Kendrick (eds.), Frontiers of Quantitative Economics, Vol. II, Amsterdam: North-Holland Press, pp. 106-171.

Emery, P. W. (1965), "An Empirical Approach to the Motor Carrier Scale Economies Controversy," Land Economics, 41.

Fisher, F. M. (1969), "Approximate Aggregation and the Leontief Conditions," Econometrica, 37, pp. 457-469.

Friedlaender, A. F., and R. H. Spady (1981), Freight Transport Regulation: Equity, Efficiency and Competition in the Rail and Trucking Industries, Cambridge, Massachusetts: MIT Press.

Friedlaender, A. F., R. H. Spady, and J. S. Wang Chiang (1981), "Regulation and the Structure of Technology in the Trucking Industry," in Cowing and Stevenson (eds.), Productivity Measurement in Regulated Industries, New York: Academic Press.

Fuss, M., D. McFadden, and Y. Mundlock (1978), "A Survey of Functional Forms in the Economic Analysis of Production," in M. Fuss and D. McFadden (eds.), Production Economics: A Dual Approach to Theory and Application, Amsterdam: North-Holland Press.

Garrison, W. L., and D. F. Marble (1965), "Graph Theoretic Concepts," in M. E. Hurst (ed.), Transportation Geography: Comments and Reading, New York: McGraw Hill.

Gordon, S. R. (1974), "Relationships between Economies of Scale and the Shape of Transportation Networks," Ph.D. dissertation, Massachusetts Institute of Technology, Department of Civil Engineering.

Gordon, S. R., and R. de Neufville (1977), "Rationalization of the European Air Net," Transportation Research, 11, pp. 235-244.

Griliches, Z. (1972), "Cost Allocation in Railroad Regulations," Bell Journal of Economics and Management Science, 3, No. 1 (Spring), pp. 26-41.

Hall, R. E. (1973), "The Specification of Technology with Several Kinds of Output," Journal of Political Economy, 31, No. 4.

Harmatuck, D. J. (1979), "A Policy-Sensitive Railway Cost Function," The Logistics and Transportation Review, 15, No. 2.

Interstate Commerce Commission (1976), Class I Motor Carriers - Annual Report.

Jara-Diaz, S. (1981), "Transportation Cost Functions: A Multi-Product Approach," Department of Civil Engineering, Massachusetts Institute of Technology, Ph.D. Dissertation (June).

Jara-Diaz, S., and C. Winston (1981), "Multiproduct Transportation Cost Functions: Scale and Scope in Railroad Operations," Massachusetts Institute of Technology, Center for Transportation Studies (March).

Kansky, K. J. (1963), "Structure of Transportation Networks," Research Paper 84, University of Chicago.

Kneafsey, J. T. (1975), Transportation Economic Analysis, Lexington, Massachusetts: Heath-Lexington Books.

Koenker, R. (1977), "Optimal Scale and the Size Distribution of American Trucking Firms," Journal of Transport Economics and Policy, 14, No. 1, (January), pp. 54-67.

Koshal, R. K. (1972), "The Cost of Trucking: Econometric Analysis," Journal of Transport Economics and Policy, 12.

Ladenson, M. L., and A. J. Stoga (1974), "Returns to Scale in the U.S. Trucking Industry," Southern Economic Journal, 44.

LaMond, A. M. (1980), Competition in the General-Freight Motor-Carrier Industry, Lexington, Massachusetts: Lexington Books, D. C. Heath and Co.

Lawrence, M. L. (1976), "Economies of Scale in the General Freight Motor Common Carrier Industry: Additional Evidence," Proceedings of the Transportation Research Forum, Vol. 17, No. 1, pp. 169-176, Oxford, Indiana: Richard B. Cross Co.

Lucas, R. E. B. (1975), "Hedonic Price Functions," Economic Inquiry, 2, pp. 157-158.

McFadden, D. (1978), "Cost, Revenue, and Profit Functions," in M. Fuss and D. McFadden (eds.), Production Economics: A Dual Approach to Theory and Application, Amsterdam: North-Holland Press.

Meyer, J. R., M. J. Peck, J. Stenason, and C. Zwick (1959), The Economics of Competition in the Transportation Industries, Cambridge, Massachusetts: Harvard University Press.

Nelson, R. A. (1956), Motor Freight Transport in New England, A report to the New England Governors' Council, Boston, Massachusetts.

Panzar, J. C., and R. D. Willig (1977a), "Economies of Scale in Multi-Output Production,," Quarterly Journal of Economics, 91, pp. 481-493.

Panzar, J. C., and R. D. Willig (1977b), "Free Entry and the Sustainability of Natural Monopoly," Bell Journal of Economics, 8 (Spring), pp. 1-22.

Plott's Oil Price Handbook, (1976).

Roberts, M. J. (1956), "Some Aspects of Motor Carrier Costs: Firm Size, Efficiency, and Financial Health," Land Economics, 32.

Roberts, P. O. (1977), "Some Aspects of Regulatory Reform in the U.S. Trucking Industry," Massachusetts Institute of Technology, Center for Transportation Studies Report 77-1.

Shephard, R. W. (1970), Theory of Cost and Production Functions, Princeton: Princeton University Press.

Spady, R. H. (1979), Econometric Estimation of Cost Functions for Regulated Transportation Industries, New York: Garland Press.

Spady, R. H., and A. F. Friedlaender (1976), "Econometric Estimation of Cost Functions in the Transportation Industries," Massachusetts Institute of Technology, Center for Transportation Studies Report 76-13.

Spady, R. H., and A. F. Friedlaender (1978), "Hedonic Cost Functions for the Regulated Trucking Industry," The Bell Journal of Economics, 9, No. 1.

Trinc Transportation Consultants (1977), Trinc's Blue Book of the Trucking Industry.

U. S. Senate, Select Committee on Small Business (1956), "Trucking Mergers, Concentration and Small Business: An Analysis of Interstate Commerce Commission Policy, 1950-1956," by W. Adams and J. Hendry.

U.S. Senate, Hearings of the Committee on the Judiciary (1980), "Federal Restraints on Competition in the Trucking Industry: Antitrust Immunity and Economic Regulation."

Varian, H. R. (1978), Microeconomic Analysis, Norton Press.

Wales, T. J. (1977), "On the Flexibility of Flexible Functional Forms: An Empirical Approach," Journal of Econometrics, 5, pp. 183-193.

Wang Chiang, S. J. (1979), "The Structure of Cost and Technology of Regulated Common Carriers of General Commodities," MS Thesis, Massachusetts Institute of Technology, Department of Civil Engineering.

Warner, S. J. (1965), "Cost Models, Measurement Errors, and Economies of Scale in Trucking," in M. L. Burstein (ed.), The Cost of Trucking: An Econometric Analysis, Evanston: Northwestern University Press.

Willig, R. D. (1979), "Multiproduct Technology and Market Structure," American Economic Review, 69, No. 2., pp. 346-350.

Wilson, G. W. (1959), "On the Output Unit in Transportation," Land Economics, 35.

Wyckoff, D. D. (1974a), "Factors Promoting Concentration of Motor Carriers under Deregulation," Proceedings of the Transportation Research Forum: 1-9.

Wyckoff, D. D. (1974b), _Organizational Formality and Performance in the Motor Carrier Industry_, Lexington, Massachusetts: Lexington Books, D. C. Heath and Co.

Wyckoff, D. D., and D. H. Maister (1975), _The Owner-Operator: Independent Trucker_, Lexington, Massachusetts: Lexington Books, D. C. Heath and Co.

Wcykoff, D. D., and D. H. Maister (1977), _The Motor Carrier Industry_, Lexington, Massachusetts: Lenxington Books, D. C. Heath and Co.

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