ECONOMIC RESEARCH REPORTS

THE STRUCTURE OF PRODUCTION, TECHNICAL CHANGE AND EFFICIENCY IN A MULTIPRODUCT INDUSTRY: AN APPLICATION TO U.S. AIRLINES

by

David H. Good

M. Ishaq Nadiri

and

Robin C. Sickles

R.R. #89-14

June 1989

**C. V. STARR CENTER
FOR APPLIED ECONOMICS**

NEW YORK UNIVERSITY
FACULTY OF ARTS AND SCIENCE
DEPARTMENT OF ECONOMICS
WASHINGTON SQUARE
NEW YORK, N.Y. 10003

The Structure of Production, Technical Change and Efficiency in a Multiproduct Industry: An Application to U.S. Airlines[1]

David H. Good
Indiana University

M. Ishaq Nadiri
New York University
and National Bureau
of Economic Research

Robin C. Sickles
Rice University
and National Bureau
of Economic Research

Revised

April 1989

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[1] An earlier version of this paper was given at the 1987 American Economic Association meetings. The authors would like to thank Frank Gollop and the participants at NBER's summer workshops on Productivity and R&D for their insightful comments. Financial support was provided in part by the C.V. Starr Center's Focal Program for Capital Formation, Technological Change, Financial Structure and Tax Policy and through a program development grant from Indiana University. Sickles funding was provided in part by the National Science Foundation.

1. INTRODUCTION

Over the last three decades economists have expended substantial effort in formulating optimizing models which take account of the inherent complexities of technology.[2] In this paper we set out an integrated model that incorporates a wide range of these features of the production process. Our purpose is to assess the sensitivity of the structure of technology to three common assumptions: cost minimizing behavior, the specification of technological change and the endogeneity of the production technique. The concept of "virtual" prices (i.e., shadow prices) is explicitly introduced in the model to allow estimation of the true technology despite potentially non-cost minimizing behavior by the firms. We explicitly formulate a multiple output technology where the choice of production technique is an endogenous decision. Finally, rather than using time as a proxy for changes in the production technique, we employ a variable cost function which explicitly incorporates characteristics of the production technique and their interactions with the variable inputs as well as dynamic effects arising from the fixity of the capital stock in the short-run.

The models which we develop are used to examine the behavior of 13 airlines between 1977 and 1981. This period is particularly interesting for our purposes since it includes both the transition to deregulation of the industry and a nearly fourfold increase in fuel prices. Both of these are likely to induce a change in the nature of output produced and/or a change in the chosen production technique. New route entry and exit authority lead to increased use of hub-and-spoke type networks. Fuel price increases encouraged

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[2] These innovations have included flexible functional forms (for a survey see Nadiri (1982)), techniques to capture very general forms of heterogeneity (e.g., Sickles (1985)), models of interrelated demand functions and temporary equilibria (e.g., Nadiri and Rosen (1969) and Pindyck and Rotemberg (1982)), models of changing expectations about future prices and outputs and the consequences of non-cost minimizing behavior (e.g., Berndt and Morrison (1981), Nadiri and Prucha (1984), Morrison (1986), Lovell and Sickles (1983) and Atkinson and Halvorsen (1984)), and structures for determining interrelationships between various outputs (e.g., Hall (1972), Baumol (1977), Brown, Caves and Christensen (1979) or Nadiri (1987)).

the retirement of older airplanes in favor of more fuel efficient aircraft types. Furthermore, different airlines used very different fleets of aircraft encouraged by past regulation, and hence, had a variety of production techniques. The effect that regulation had on the choice of technique has been described extensively.[3] Protection from competition on high density routes allowed the trunk airlines to adopt large widebodied jets. Subsidies provided to the local service carriers allowed them to use more expensive jet equipment than was economically justified for their routes. After deregulation, airlines were left with equipment acquisitions encouraged at a time when there was limited market entry and subsidized service.

We organize our treatment of these issues in the following way. In section 2 we formulate the optimization framework of a multiple output firm using a translog variable cost function. The flexible production process has arguments which include two measured outputs (scheduled passenger and other revenue ton mile service), three output characteristics (average stage length, number of scheduled stations, and a measure of connectedness of the network), three measured variable inputs (labor, energy, and materials), one measured fixed input (capital), and five characteristics of technology (average age of the fleet, average speed, convertiblity of the fleet between cargo to passenger, average aircraft size, and a measure describing the diversity of aircraft sizes within the fleet). Section 3 generalizes the multiple output variable cost model by explicitly allowing non-cost minimizing decisions and presents some institutional rationale for such behavior. We generalize the basic model by parameterizing a divergence between virtual prices and observed prices and hence between observed cost and shares and virtual cost and shares. This model extends previous work by allowing the array of technologies used by

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[3] See Eads (1974), Phillips (1972) and Bailey, Grapham and Kaplan (1985).

the firm to be choice variables. Consequently, characteristics of the technology, output levels and output characteristics are allowed to exhibit *ex post* correlations with other endogenous variables. Although our extended model introduces substantial nonlinearities, it allows one to analyze the extent to which distortions in cost-minimizing behavior may be an artifact of the treatment of empirical proxies for technical change as well as its endogeneity. To do this, we compare excess costs due to allocative distortions in a model in which technology is treated by standard proxies such as time and is exogenous with the measured inefficiency costs generated by our model. To the extent that these are different, it reveals a misspecification in previous studies based on more restrictive models.

Section 4 describes cross-sectional time-series data on airlines for the period 1977 I-1981 IV. Section 5 briefly outlines the strategy for estimating the undistorted and distorted cost and share systems and discusses estimation results for our most general model. In section 6, comparisons are made between our most general model and several less general models. The degree of potential economies of scale and scope, the elasticities of demand for variable inputs, the degree of complementarity or substitution among inputs and outputs, and the factors determining the technological attributes of the production process are discussed in detail. The last section of the paper summarizes our results and points to several areas for further research.

2. THE BASIC MODEL

In our basic model the distortions due to regulation are not formally addressed. We assume that airlines employ inputs, $X > 0$, and allow some inputs (notably, aircraft fleets) to be fixed. In general, let these fixed inputs and their characteristics be the last N-J elements of X which we write as $X = \{X_J, X_{N-J}\}$. The firm employs these inputs to produce outputs $Y = \{y_1, \ldots, y_m\}$

and we allow some outputs, e.g., service, to be unobservable and proxied by a number of attributes. Let these unobserved outputs be the last M-K elements of Y which we write as $Y = \{Y_K, Y^*_{M-K}\}$. The production possibilities set T is assumed to satisfy the following regularity conditions:

(T.1) T is a non-empty subset of Ω^{m+n}, and if $(Y,-X) \in T$, then $Y \geq 0$.

(T.2) T is a closed set which is bounded from above.

(T.3) T is a convex set.

(T.4) If $(Y, -X) \in T$, then $(Y^*, -X^*) \in T$ for all $0 \leq Y^* \leq Y$; $X^* \geq 0$.

The variable cost function, i.e., the minimum variable cost that can be obtained by adjusting the J variable inputs with strictly positive input prices W_J where $W = \{W_J, W_{N-J}\}$, is

(2.0) $C(Y,W_J;X_{N-J}) = \inf\{W_J X_J^T: \ (Y, -X) \in T\}$.

The production unit's variable cost function inherits its properties from T and the solution to the program in (2.0). These properties are:

(C.1) C is a non-negative real-valued function defined for all strictly positive (Y, W_J) and nonnegative X_{N-J}.

(C.2) C is non-decreasing in Y and non-increasing in W_J for $X_{N-J} \geq 0$.

(C.3) C is positively linearly homogeneous, concave, and continuous in W_J.

With the aid of Shephard's Lemma, we can obtain the variable input demand equations by

(2.1) $\nabla_{W_J} C = X(Y, W_J; X_{N-J})$.

Our basic model differs from those typically employed to model short-run technologies in that we have been deliberately general as to how the menu of production techniques is to be modeled. One frequently used approach is to model changes in the technique with a time proxy. An alternative is to model the menu of production techniques with a set of attributes of the fixed inputs, notably, characteristics of the aircraft fleet. To implement our model we consider five attributes of the capital stock: vintage age, size, diversity in size, convertibility, and average cruising speed. These characteristics affect the flexibility of the carriers to fit demand for capacity to particular equipment configurations. We expect newer aircraft types, all other things equal, to be more productive than older types. Newer wing designs, improved avionics, and more fuel efficient engine technologies make the equipment more productive. Once a design is certified, a large portion of the technological innovation becomes fixed for its productive life.

In an engineering sense, all transportation industries are characterized by increasing returns to equipment size. Costs for fuel, pilots, terminal facilities and even landing slots can be spread over a larger number of passengers. However, large size is not without potential economic penalties. As the equipment size goes up it becomes increasingly difficult to fine tune capacity on a particular route. Also, as this capacity is concentrated into fewer departures, the quality of service declines (the probability that a flight is offered at the time that a passenger demands it decreases). This raises particular difficulties in competitive markets where capacity must be adjusted in response to the behavior of rival carriers. Deregulation has accentuated this liability by virtually eliminating monopolies in domestic high density markets. In any event, the operating economies of increased equipment size must be traded off for this limited flexibility.

Fleet diversity again represents tradeoffs. One would expect that having different sizes of aircraft would allow the carrier to obtain a better fit between the demands for capacity on a particular route and the type of equipment used. On the other hand, there has been a major trend toward increased standardization of fleets. Having a single aircraft type minimizes the inventory of spare parts as well as maintenance and crew costs.

Airframe manufacturers have offered three innovations in response to the daily, weekly and seasonal peaks in demand for passenger service: quick change aircraft, convertible aircraft and combination aircraft. Aircraft with the quick change option were designed to allow conversion from passenger service to cargo operations in about one hour. This made it available for passenger service during the day and cargo operations at night - greatly increasing its potential utilization. Regular convertible aircraft could be changed so that they were available for passenger service on peak days, and available for cargo passengers and cargo to be carried on the main deck, often with a movable partition between them.

One of the most significant contributions to productivity growth in the 1960's was the advantage of increased speed brought along with jet equipment. While this innovation was widely adopted, it was by no means universal for carriers in our sample.

We also include two measured outputs: scheduled and nonscheduled service, three variable inputs: labor, fuel and materials (an aggregation of supplies and outside services), and three attributes of airline networks: the stage length, the number of cities serviced and the extent of network connectivity. Stage length allows us to account for differing ratios of cost due to ground-based resources to costs attributable to the actual length of the flights. Short flights use a higher proportion of ground based systems than do longer flights for a passenger-mile of output. The number of stations to which the airline provided scheduled service provides an alternative measure of network size. Carlton, Landes and Posner (1980) suggest that airlines serving a larger number of cities provide a higher quality of service since interlining of passengers is less likely.

Finally, we provide further detail about output by including a measure of network connectedness. This allows us to control for airline's decisions to make increased use of hub-and-spoke and loop type networks. These innovations allow carriers to increase load factors, but they artificially inflate the level of real production by increasing the air miles between cities and by reducing the likelihood of non-stop service.

3. THE EXTENDED MODEL

In our extended model[4] we further generalize our capital attribute model of technology by allowing the firm to operate at the wrong point on the boundary of its production possibility set, given the output and input prices it faces and the behavioral objective of cost minimization. Consequently, the assumption of cost minimization is a testable, rather than an *a priori*, conjecture. The presence of allocative inefficiency as a measured phenomenon can be due to a number of factors. One is that there is in fact suboptimal decision making by the firm in setting its relative output and input mix (true allocative inefficiency). Another is that the econometric model used in the measurement process is misspecified (spurious measured inefficiency). Although there are several different potential misspecifications, the differential impact of CAB regulation leads us to focus on a small set of interrelated factors which we believe to be first order problems. These include the incorrect imputation of the capital service price and quantity index and the timing of capital purchase decisions. We also allow for the choice of technique, broadly defined, to be a decision that is affected by both input and output markets. As a first step in this analysis we allow for distortions to exist in the measured variable inputs. The focus on this limited source of distortion stems from our wish to distinguish between systematic and nonsystematic impacts of regulation. In particular, we believe

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[4] Our extended model is based on the work of Toda (1976), Lovell and Sickles (1979), Atkinson and Halvorsen (1984), Sickles, Good, and Johnson (1986), and Eakin and Kniesner (1988). It can also be viewed as a dual approach to other parametric inefficiency models.

that CAB regulation led to systematic distortions in the combinations of inputs that were used (such as the overuse of labor) but it led to nonsystematic impacts in the combinations of outputs that were produced and in the kind of capital stock that was chosen.[5]

The CAB's mandate of maintaining the financial viability of the industry provided all carriers with protection from competition by the creation of barriers to entry. Much of the principal-agency literature suggests that protection allowed managers to use their discretionary behavior to pursue nonprofit maximizing objectives. In particular, expense preference theory suggests that managers could gain the approximate equivalent of promotion by hiring excess employees.[6]

Kahn (1971) also describes how the technological change which occurred during the 1960s and early 1970s combined with collective bargaining practices to encourage a distorted use of labor. Not all innovations have led to cost reductions. Flight crew salaries for new equipment were based on the salaries that would have been earned using the less productive older equipment. This meant that benefits from the increased speed of jet equipment was partially offset by basing salaries on a "pegged speed" for the aircraft (much lower than the speed planes actually flew). Similarly, productivity gains of increased size (adoption of wide bodied jets) during the 1970s were also partially captured by flight crews. On the other hand, some other technological advances resulted in the elimination of personnel. Improvements in radio and navigational equipment led to the elimination of radio operators and navigators with those duties picked up by the pilots. Improved avionics

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[5] Treating output distortions differently from input distortions is reinforced by the CAB's often heavy-handed discretion regarding entry and exit granted to them by the Federal Aviation Act of 1958, while they had no authority whatsoever in dictating the decisions about choice of capital, decisions regarding employees or the type of service being offered (e.g., passenger food).

[6] Williamson (1963) also describes this behavior as "feather bedding," "empire building" or "satisficing." It is discussed in more detail for airlines in Good (1987).

during the 1970s led to the gradual elimination of engineers (leaving a two person flight crew) on most small jets (BAC111, DC9s and B737s). Together with expense preference behavior, this strongly suggests an overuse of labor given its actual wage rate.

CAB regulation provided other distortions in firm behavior, notably excess flight frequency (service competition). However, because of its multi-tiered regulatory system, the CAB's policies affected airlines differentially during the study period with respect to these decisions.[7] When the differential restrictions were eliminated by deregulation, the different classes of carriers were, quite naturally, left with very different types of capital stocks. Casual observation shows that the former local service airlines were much more profitable during the transition than the former trunks. Further, studies by Caves, Christensen and Tretheway (1983) and Bailey, Graham and Kaplan (1985) suggest that the productivity growth of the former local service carriers was much higher than that of the trunks during the transition to deregulation. While the local service airlines had aircraft that were too large for use in their low density routes under regulation, they were ideal for the newly deregulated environment. On the other hand, while the large wide-bodied aircraft of the trunks were ideal in their protected high density markets under regulation, they were inappropriate for the deregulated environment since most of the new entry was manifested on high density routes.

We introduce distorted cost-minimizing behavior into our model by rewriting the cost minimization requirement that input's x_i and x_j be hired in combinations that equate their marginal rate of technical substitution with

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[7] The multitiered system, similar to that of the banking sector, segregated carriers into 6 distinct classes, each with its own "mission." The two classes included in our study are the truck and the local service airlines. Trunk airlines, originally certified in 1938, were given the responsibility of providing most long haul service. Local service airlines, certified in the period from 1945 through 1955, were originally conceived of as providing "feeder" service for the trucks. These distinctions began to blur as the CAB began certificating local service airlines on medium haul profitable routes to offset the growing level of subsidy necessary for feeder service during the 1960s and early 1970s.

their observed price ratio. Consider the production function $F(Y,X) \leq 0$ characterized by the technology set T and let virtual prices diverge from observed prices by an amount $\theta = \{\theta_1,\ldots,\theta_N\}$. Then the cost-minimizing conditions in terms of the virtual (shadow) prices of input pair i,j is

$$(3.0) \qquad w_i^*/w_j^* = \frac{\partial F/\partial x_i}{\partial F/\partial x_j} \qquad \text{where } w_i^* = w_i + \theta_i.$$

Corresponding to the observed cost function defined in (2.0) when there is no divergence between observed and virtual (shadow) input prices is the virtual cost function $C^*(Y,W_J^*;\ X_{N-J})$. Factor demands derived from the firm's minimum virtual cost function are given by

$$(3.1) \qquad X_J^*(Y,W_J^*;\ X_{N-J}) = \nabla_{W_J^*} C^*(Y,\ W_J^*;\ X_{N-J}).$$

The observed variable cost function and associated short-run factor shares are

$$(3.2) \qquad C(Y,\ W_J^*,\ W_J;\ X_{N-J}) = W_J^T X_J^*$$

and

$$(3.3) \qquad M_i = w_i x_i / C(Y,\ W_J^*,\ W_J;\ X_{N-J}),\ i = 1,\ldots,J.$$

Since virtual shadow cost shares are $M_i^* = \partial \ln C^*/\partial \ln w_i^* = w_i^* x_i/C^*$, observed input use can be related to virtual prices and quantities by $x_i = M_i^* C^*/w_i^*$. Observed costs can then be re-expressed as

$$(3.4) \qquad C = C^*[\sum_i (M_i^* w_i/w_i^*)]$$

and observed factor shares can be re-expressed as

$$(3.5) \qquad M_i = (M_i^* w_i/w_i^*)/\sum_j (M_j^* w_j/w_j^*)\ .$$

The empirical vehicle for examining distortions in input allocations is the translog variable cost function amended to incorporate input and output characteristics. Included among these are characteristics of technology which may react to changes in market conditions and/or short-run and long-run changes in input substitution and output transformation possibilities. The virtual variable translog cost function $\ln C^*$ is given by

$$(3.6)\qquad \ln C^* = \alpha + \sum_i \alpha_i \ln y_i + \tfrac{1}{2} \sum_{ij}\sum \alpha_{ij} \ln y_i \ln y_j + \tfrac{1}{2} \sum_{lm}\sum \gamma_{lm} \ln y_l \ln(w_m+\theta_m)$$

$$+ \tfrac{1}{2} \sum_{no}\sum \upsilon_{no} \ln y_n \ln x_{J+0-1} + \sum_i \beta_i \ln(w_i+\theta_i) + \tfrac{1}{2} \sum_{pq}\sum \beta_{pq} \ln(w_p+\theta_p) \ln(w_q+\theta_q)$$

$$+ \tfrac{1}{2} \sum_{rs}\sum \lambda_{rs} \ln(w_r+\theta_r) \ln x_{J+S-1} + \sum_i \rho_i \ln x_{J+i-1} + \tfrac{1}{2} \sum_{tu}\sum \rho_{tu} \ln x_{J+t-1} \ln x_{J+u-1},$$

where we have suppressed the "*" notation for the service attributes contained in the last M-K elements of the output vector Y and do not distinguish notationally between measured quantities of quasi-fixed inputs and characteristics of the chosen technology.

Virtual cost shares are given by

$$(3.7)\qquad M_i^* = \beta_{ii} + \sum_j \beta_{ij} \ln(w_j+\theta_j) + \sum_j \gamma_{ji} \ln y_j + \sum_j \lambda_{ij} \ln x_{J+j-1}.$$

The observed cost and share system in terms of the parameters of the virtual technology are

$$(3.8)\qquad \ln C = \ln C^* + \ln[\sum_i \{(\beta_{ii} + \sum_j \beta_{ij} \ln(w_j+\theta_j) + \sum_j \gamma_{ji} \ln y_j + \sum_j \lambda_{ij} \ln x_{J+j-1})w_i/(w_i+\theta_i)\}]$$

$$(3.9)\qquad M_i^* = M_i w_i/(w_i+\theta_i)/[\sum_j (\beta_{ii} + \sum_k \beta_{jk} \ln(w_k+\theta_k) + \sum_k \gamma_{kj} \ln y_k + \sum_k \lambda_{jk} \ln x_{J+k-1})w_j/(w_j+\theta_j)].$$

Symmetry and linear homogeneity in input prices are imposed on the virtual shadow cost function by restrictions of the form

$$\alpha_{ij} = \alpha_{ji},\ \forall i,j;\ \beta_{ij} = \beta_{ji},\ \forall i,j;\ \sum_i \beta_{ii} = 1,\ \sum_j \beta_{ij} = 0,\ \sum_j \lambda_{ij} = 0,\ \forall i \quad \gamma_{ij}=0, \forall i.$$

Summary statistics are provided by the Allen-Uzawa elasticities of substitution between inputs and related measures of own demand elasticities, and several measures of returns to scale which extend from the short-run to the long-run. These are all expressed in the standard fashion for the virtual translog and its associated virtual share equations since it, rather than the observed model, describes the true underlying technology. A measure of excess costs due to the divergence of virtual and measured prices is given by the difference between observed ln C and estimated ln C for which $\theta = 0$. Any divergence between observed and virtual price for any input will cause this difference to be positive.

Our interest in this system of equations lies in its ability to nest competing models whose comparability may be compromised by a less general modeling scenario. We need not worry about contaminating our conclusions by not controlling for dynamics in the adjustment of capital, nor need we be concerned about misspecifying the capital service variable. We simply treat its many dimensions as variables on which we condition the technology.

We allow for output and its characteristics and capital and its characteristics to be *ex post* choice variables and thus for purposes of estimation, endogenous. We posit approximations to their implicit reduced forms which are homogeneous of degree zero in input prices. The exogenous variables in the reduced forms are input and output prices, time, and seasonal dummy variables. The endogeneity of technological characteristics arises from the notion that an air carrier optimizes not only to obtain the appropriate multiple input mix but also to select the correct configuration of the technological characteristics of the fleet and the type of service its fleet is being chosen to serve. The choice of these characteristics will depend on the market prices and trade-offs between the benefit and costs of different technological features of the fleet and various dimensions of its routes. Reduced-form responses of output and input characteristics to changes in relative virtual prices can be determined by examining the reduced-form estimates. Furthermore, patterns of price responses can be correlated with implied shadow prices to better understand substitution possibilities among the quasi-fixed input and its characteristics, and the output characteristics.

4. DATA

The data follow 13 domestic air carriers with quarterly observations between 1977 and the end of 1981. These firms are the set of former certificated carriers that existed throughout the study period and account for well over 95 percent of the domestic air traffic. There are two notable exceptions. Pan American and Trans World were excluded because a very large part of their traffic is generated in international markets with a different set of regulations, often established by treaty. Northwest experienced a number of strikes over the period and provided nonsystematic reporting of personnel and aircraft assigned to service during those periods. When firms merged, only one firm (the largest) was kept in the sample prior to the merger. Consequently, Southern, National and Hughes Airwest were dropped in order to maintain a balanced panel. Mergers were viewed as simple acquisitions of additional resources by the dominant firm. The remaining airlines are American, Allegheny (U.S. Air), Braniff, Continental, Delta, Eastern, Frontier, North Central (Republic), Ozark, Piedmont, Texas International, United and Western. Information on prices and quantities for these airlines was obtained from the CAB Form-41 reports for over 250 separate categories of expenditures, revenues, inputs and outputs. These were aggregated into five broad input indices and two broad output indices using a chained variant of the Tornquist-Thiel multilateral index number procedure. A detailed discussion of this data is contained in previous work (Sickles, et. al. (1986)). The input aggregates are capital (K), labor (L), fuel (E) and a residual (designated materials) incorporating supplies and outside services (M). The output aggregates are scheduled passenger (Q1) and other nonscheduled services (Q2, cargo and charter operations).

We add to this data on the network structure and capital characteristics. Stage length, (S), was constructed by dividing aircraft miles flown by the number of takeoffs, both Form 41 variables. The number of cities serviced, (N), was taken from the Official Airline Guide. Our measure of network connectedness, (H), divides the total number of route segments by the maximum possible number of routes for those cities served.

Data on technological characteristics were collected for individual aircraft types from Jane's (1945 - 1982 editions). The number of these different aircraft types in each airline fleet was collected from the CAB Form-41 Schedule T-2. Aircraft that were for predominately corporate use (rather than to provide revenue generating service) were excluded.

We use the average number of months since FAA type certification of aircraft designs as our measure of fleet vintage (A1). Our view is that the technological innovation in an aircraft does not change after the design is type certified. Consequently, our measure of technological age does not capture the deterioration in capital and increased maintenance costs caused by use. Our measure does capture retrofitting older designs with major innovations, if these innovations were significant enough to require recertification of the type.[8]

Average equipment size (A2) was measured with the highest density seating configuration listed in Jane's for each aircraft type. This average across

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[8] For example, the original Convair 240, used by many of the trunk airlines during the 60's, was originally a piston powered aircraft with certification date of March 1953. These planes were retrofitted with much more fuel efficient and powerful Allison turboprop engines and recertified as a Convair 580 in February 1960. Later variants involved retrofitting with still more fuel efficient Rolls Royce Dart turboprop engines (as well as other modifications in avionics and to the wing) and recertification as a Convair 640 in March of 1966. These aircraft were still in use by some of the former local service airlines during the study period.

the fleet was weighted by the number of aircraft of each type assigned into service. In some cases, particularly with wide-bodied jets, the actual number of seats was substantially less than described by this configuration. This definition caused problems with some aircraft that only had cargo civilian applications (such as the Lockheed Hercules). In these cases, military equivalent passenger counts were used (i.e., troop transports). The diversity of equipment sizes (A3) was constructed with a Gini coefficient. The higher the value of our measure, the lower the diversity of equipment sizes.

We operationalize our measure of fleet flexibility (A4) by using the fraction of aircraft in the fleet which were designated as either combination aircraft, quick change aircraft or convertible aircraft.[9] Limitations of CAB reporting made it impractical to separate the individual categories. Finally, the average economy cruising speed was used to measure fleet speed (A5).

5. ESTIMATION, SPECIFICATION AND RESULTS

Our first order of business is to select a parameterization of technology that is general enough to address the issues we are concerned with but at the same time is parsimonious. Our short-run technology has three variable inputs, one fixed factor, five technology characteristics, two measured output quantities, and three output service characteristics. We control for cost neutral seasonal variations by including three seasonal dummy variables in the cost equation. We also control for fixed firm effects by including firm dummy variables in the cost equation. A second order translog approximation to the cost function (3.6) would have 110 free parameters. With 13 firms and 20 time-series observations a restricted form of (3.6) must be found. Our stopping rule is somewhat arbitrary but does allow for a fairly general

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[9] This aggregation seems appropriate since in practice quick change aircraft took longer than planned to change over and had higher labor costs than expected, making their daily conversion impractical.

structure. We allow for all second-order effects except those involving only attributes of service and of the technology as well as interactions between the service characteristics and measured revenue ton miles of scheduled and other service. Thus $\rho_{kAi}=0$, $i=1,5$ and $\alpha_{ij}=0$, for $i=Q1,Q2$ and $j = S,N,H$. We still are able to construct shadow prices of the output and technology attributes, but we assume that any variation in these shadow prices due to variations in measured outputs, the quasi-fixed capital stock, or in other attributes have second-order effects which can be neglected.

We wish to consider the sensitivity of our results to three modeling assumptions: the specification of technological change, the assumption of cost minimizing use of inputs, and the assumption of exogeneity of products and production techniques. The interactions between these three different specifications leads to the eight models displayed in Table 1.

Our first distinction is between models which assume an allocatively efficient use of inputs and those that do not make such an assumption. These specifications are represented by our basic model (equations 2.0 and 2.1) and our extended model (equations 3.8 and 3.9).

The second specification issue deals with how technological progress should be specified. Again, we consider two possibilities: the commonly used time proxy specification and our capital attribute specification. In the basic specification, we proxy technological change over time with time itself. In our capital attribute model we allow firms to choose from a menu of different production technologies (choice of aircraft) that are explicitly described in the model. Technological change is captured by how the adopted production technique changes over time.

Our third specification issue deals with endogeneity of output, its characteristics and of the production technique. We consider two estimators: the commonly used iterated seemingly unrelated regression method (Zellner, 1962), and the generalized method of moments (Hansen and Singleton, 1982). We allow the outputs, output characteristics, quasi-fixed inputs and the production technique to be endogenous. Instruments for these endogenous variables are constructed from input and output prices, seasonal dummies and time and from their interactions. We further impose the logical restriction that the functional form for these instruments is homogeneous of degree zero in prices. Because our extended model is inherently nonlinear, we employ the nonlinear analogues of these methods when estimating the distorted production models.

In addition to the parameter estimates in Table 1, derived properties of the efficient production technology for our set of models are presented in Table 2. The list of derived properties includes short-run returns to scale, returns to route density, and returns to network size measures[10], Allen-Uzawa elasticities of substitution, patterns of allocative inefficiency, a decomposition of technological change (described in the appendix), Hausman tests for endogeneity and the ratio of the Jorgensen-Hall user price of capital to its estimated shadow price.

All models converged quite quickly and without incident with the exception of the inefficient-time proxy-seemingly unrelated regression model.[11] The results for our most general model are quite sensible. From the derived properties in Table 2, we find that at sample mean prices and quantities there is a moderately inelastic demand for labor (0.323) and materials (0.423), and a very inelastic demand for energy (0.016). The short-run elasticity of

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[10] Our short-run measure of returns to scale is defined to be the inverse ray elasticity of cost for our two outputs. The returns to route density measure is defined to adjust for a quasi-fixed capital stock as in Brown, Caves and Christensen (1979) though it holds the network attributes constant as in Caves, Christensen and Tretheway (1984). Our returns to network size is defined to be the inverse of the sum of cost elasticities for outputs, capital stock and the number of route segments. It can be interpreted as the effect of attempting to scale up output by increasing the number of route segments, while maintaining a comparable traffic density on each route.

[11] This model generated very high standard errors for the estimated parameters and produced unbelievably large results for the distortion parameters. Despite repeated attempts, even using the more robust estimates from the corresponding generalized method of moments model as starting values, the same optimum was consistently achieved.

substitution between labor and materials is 0.987. This stems from the ability to substitute labor within the firm for outside labor services (predominately contract maintenance and travel agent commissions). There is also modest substitutability between materials and the energy input (η=.6033). Again, this is likely to reflect the use of outside maintenance and spare parts.

Short-run returns to scale are rather high with an average value of 2.174. While on the surface this seems excessive, it is mainly due to large fluctuations in demand coming from our quarterly data and, because the capital stock and network are held fixed, merely reflects the low incremental cost to increasing load factor. Our second returns to scale estimate, 1.422, is comparable to what Caves, Christensen and Tretheway (1984) have called "returns to density." This measure allows us to assess what happens to cost as we increase output holding the network and it characteristics fixed. It is somewhat higher than their estimate of 1.24. The primary difference between these values is that our inclusion of the connectedness measure allows us to more clearly identify the returns to increasing output at the route level. Finally, our third returns to scale estimate of .888 is based on changing output, the capital stock and the number of new cities to which service is offered, while maintaining the same level of network connectedness. This estimate is lower than the Caves, Christensen and Tretheway value of .998, and is significantly different from 1. However, this again reflects the importance of being specific as to how cities are added into the network. It also suggests that airlines can increase the number of cities served only by increased use of hub-and-spoke type networks and consequently, only at the expense of more indirect routing and lowered product quality.

Since a flight provided for passenger service is also, to some extent, available for cargo operations, it is expected that there will be cost complementarity. This is reflected by a second derivative of cost with respect to the two outputs that is negative and 5.4% of variable cost.

As anticipated, we find a modest overuse of labor and an underuse of materials. Labor is hired at approximately 8% over its cost minimizing level and materials are underhired by 13%. This is consistent with airline managers and unions keeping labor services inside the firm even though they are available at lower costs through outside contracting. It is also consistent with our discussion of expense preference behavior and the capturing of technological change in work rules. Energy is hired by only 1.6% over its cost minimizing level.

While not always statistically significant at conventional levels, the impacts of our capital attributes on cost all have the expected signs. Increases in age, diversity and speed leads to cost increases. Increased aircraft size leads to large statistically significant reductions in cost. Increases in aircraft convertibility also leads to cost increases, explaining their reduction in popularity.

The capital attributes also appear to be quite important in describing the cost shares of other inputs. In particular, we find that increased aircraft size is both labor and energy saving. These inputs can be spread across more passengers. Increased age is labor using but energy saving. This reflects the fact that a major difference between turboprop and jet equipment is age. While the small turboprops in the fleet are quite old, they are also quite fuel efficient. Surprisingly, increased speed is energy saving but labor and materials using. As expected, increased homogeneity of the fleet is labor and materials saving and consequently indicates an increased share of expenses on energy.

There was also some discrepancy between the measured price for capital and its shadow price. At median sample values we find a shadow price of capital that is approximately 14% higher than its measured price. This indicates either an incorrect imputation of the service price using conventional formulae or it indicates that the capital stock was smaller than dictated by cost minimizing behavior. This last rationale is somewhat at variance with the conventional belief that by fostering service competition, regulation led to overcapitalization. Still, there is some reason to believe that airlines were in fact slightly undercapitalized during our study period. Spot market prices for DC-9's and Boeing 737's were up to 30% higher than their long-term leased prices during our sample period. These planes constituted the largest segment of the airline fleets in our sample. Furthermore, utilization rates during our study period reached unprecedented levels for this type of equipment. On the other hand, spot market prices for large wide-bodied jets fell in an equally dramatic fashion (Graham and Kaplan, 1982, pp.173-175).

Figure 1 compares the estimated total factor productivity (TFP) growth derived from our model with the multilateral index number for TFP. The patterns over time are quite close. On average, the index number method describes a 0.9% per quarter growth in TFP while our general model estimates a 1.2% per quarter growth rate. The time path for our decomposition of productivity growth is presented in Figure 2. Network changes between the summer of 1978, just prior to deregulation, and the summer of 1979 led to a reduction in TFP of approximately 2%. This was the result of the addition of new routes by several carriers. After the summer of 1979 TFP growth stemming from changes in airline networks increased by approximately 1.6% per year, a result of route pruning and reductions in network connectedness.

While highly variable, the portion of TFP that was attributed to the distortion of inputs was increasing at the beginning of the sample (a negative contribution to TFP growth) but centered around no change later in the time series. This suggests that the additional distortions in input use which occurred prior to deregulation were not reduced as a consequence of the increased focus on price competition.

The pattern of technological change was very near zero through the entire period with two exceptions. As older equipment was brought back into service following deregulation, TFP declined. However, after the oil price shock in 1979, there was a one period .5% increase in TFP growth as the older, less fuel efficient aircraft were again retired. This is again quite consistent with less systematic evidence indicating little technological change. The equipment designs available had been in production since the early 1970s. The new generation of more fuel efficient designs, Boeing 757 and 767 and the McDonnell-Douglas 80s did not come into service until 1982. While there was a large increase in demand for new aircraft, its primary impact was to increase the waiting time for new planes rather than to increase the number delivered.

6. MODEL COMPARISONS

The first of the specification issues that we examine is endogeneity. Where possible, Hausman-Wu tests were conducted. In each case, exogeneity was clearly rejected. As we considered the more general specifications of technology, the rejection became less decisive. This suggests that at least part of what passes for endogeneity in simpler models, is really attributable to either distortion of input choices or misspecification of the technology by ignoring important capital attributes. The capital attributes had quite different coefficients across models, with the impact of age changing to the correct sign in our GMM models.

Our data set includes a very wide range of price and output levels over this five year period. Energy prices vary by a factor of nearly 4. Output levels for scheduled services vary by a factor of 57 with large seasonal fluctuations. Output levels for nonscheduled services vary by a factor of over a hundred. Estimated elasticities of substitution are low for some input pairs and rather high for others. Although it will be difficult for the translog to provide a regular representation of technology over these diverse conditions (Christensen and Caves, 1980), we do expect that more correctly specified models will involve fewer regularity violations than less correctly specified models. We find the capital attribute models have about 10 fewer input concavity violations than do time proxy models. While this may not seem to be an important difference, the dramatic price rises for fuel occurred quite quickly. Consequently, the range of prices satisfying regularity is substantially larger for our capital attribute specification. There is not an appreciably large difference between distorted and nondistorted models for input concavity. Surprisingly, the seemingly unrelated regression model for our distorted capital attribute model does significantly better than its generalized method of moments counterpart. The remainder of regularity violations can be attributed to a negative marginal cost for nonscheduled services.

We also reject cost minimizing behavior in our capital attributes models. Airline managers behave as though the price of labor is 29% lower than its measured price. For the time proxy specification, the standard errors on the distortion parameters are three times larger than with our capital attributes specification. Further, with 240 regularity violations out of 260 observations, it is doubtful that this is a meaningful test.

Our most general model also produced lower short-run returns to scale and returns to density measures than any other model. In fact for our general model, the short-run returns to scale are 20% lower than the model using time as a proxy for technological change and 17% lower than the model assuming efficient purchases of inputs. Both comparisons are significantly different at the 10% level. Returns to density are approximately 13% higher with either the time proxy or efficient allocation restrictions than in our general model.

Here again, the point estimates produced by less general specifications lie outside a 95% confidence interval for returns to density for our preferred model. Returns to network size are roughly comparable across the set of estimated models, ranging between .863 and .936.

Our finding of cost complementarity between scheduled and nonscheduled services is significantly demonstrated only in the capital attribute SUR models with an estimate of -6% of variable cost. While the estimates for the GMM models were quite close to the SUR estimates, the larger standard errors prevented statistical significance. In contrast, the distorted GMM time proxy model estimated cost complementarity at only 1% of variable cost. The efficient GMM time proxy model actually estimated that costs would increase by 1% if both types of services were offered.

A consistent pattern also emerges for total factor productivity growth and technological change. Our index number method produced a quarterly growth in TFP of 0.9%. Several of the models grossly exaggerate this growth rate. The efficient time proxy model estimates twice the TFP growth as the index number method and is 50% larger than our distorted capital attributes GMM model. The assumption of cost minimizing behavior increased TFP growth by 20% over that estimated by our general specification. This difference is captured by our assessment of TFP growth due to price distortion of -.22% per quarter. Finally, endogeneity accounts for 10% of the difference through its effect on the estimated impacts of the capital attributes.

These discrepancies are even larger when we consider technological change. Technological change is estimated to be ten times larger in the efficient time proxy model than in our distorted capital attributes model. It is estimated to be three times larger when the choice of technique is considered to be exogenous.

Our distorted capital attribute GMM model also shows the lowest measured distortion in the use of our quasi-fixed input. Imposing exogeneity more than doubled the level of discrepancy between the user price and the shadow price for capital. Measuring technological change with the time proxy more than tripled this difference.

7. CONCLUDING REMARKS.

We have considered a very general specification of technology in which both short- and long-run input decisions may not correspond to their equilibrium levels, and in which firms have a choice among a menu of technologies. Our most general model produced very sensible results for returns to scale and cost complementarity, and also found an overuse of labor. It produced estimates of TFP growth that were quite close to those based on the index number approach.

Our results suggest that specification of technique is quite important in describing the structure of technology, technological change, and the measurement of inefficiency. All of the characteristics of our model seem to be important. Exogeneity was always rejected. Allowing for potential distortion in variable inputs had large effects on the pattern of substitutability, in achieving agreement between the shadow price of capital and its measured user price, and in providing a specification of technology flexible enough to satisfy regularity conditions. Specifying technology with the attributes of the technique rather than using a time proxy led to significant changes in returns to scale, returns to density and cost complementarity. Even in instances where the differences between our models were not statistically significant, they were large enough to be considered substantively important. The overall pattern of our results suggest that what often passes for distortion or technological change may simply be an artifact of an overly restrictive assumptions regarding managerial choices.

APPENDIX: A DECOMPOSITION OF TECHNOLOGICAL CHANGE

Several authors have shown that when there are increasing returns to scale, or when a regulatory constraint is binding, standard total factor productivity estimates misrepresent the technological change that has occurred. Here we outline the appropriate decomposition of technical change in which the choice of technique is endogenous and observed input levels may be suboptimal.

Using a Divisia index number method, total factor productivity growth is computed to be

$$\dot{TFP} = \Sigma R_i\dot{q}_i - \Sigma M_i\dot{x}_i - M_k\dot{k} \tag{A.1}$$

where R_i is the observed revenue share of output i and M_j is the observed expenditure share for input j. Hence k is the quasi-fixed level of the capital input. Adapting an approach by Denny, Fuss and Waverman (1981) to allow for the quasi-fixed input, nonoptimality in the level of input utilization and a set of output characteristics, the observed variable cost function is

$$C^v(\underset{\sim}{q},\ \underset{\sim}{w},\ \underset{\sim}{z},\ k,\ \underset{\sim}{y}). \tag{A.2}$$

The growth rate of observed cost is

$$\dot{C}^v = \Sigma\ \varepsilon_i\dot{q}_i + \varepsilon_k\dot{k} + \Sigma\ \eta_i\dot{z}_i + \Sigma\ \frac{\partial \ln C^v}{\partial \ln w_i}\ \dot{w}_i + \dot{T} \tag{A.3}$$

where T describes the rate of cost diminution due to changing technology (changes in the growth rate of capital characteristics or time). In addition to the appearance of terms for capital and output characteristics, this differs from other decompositions because the cost elasticity with respect to input prices is not necessarily the expenditure share because of the potential for allocative inefficiency. Instead, this term can be decomposed into

$$\frac{\partial \ln C^v}{\partial \ln w_i} = M_i^v + D_i. \tag{A.4}$$

Since $C^v = \Sigma\, w_i\, x_i$, the growth rate of observed variable cost can also be described by

$$\dot{C}^v = \Sigma\, M_i^v \dot{w}_i + \Sigma\, M_i^v \dot{x}_i . \tag{A.5}$$

A bit of algebra reveals that

$$\Sigma M_i^v \dot{x}_i = \Sigma \varepsilon_i \dot{q}_i + \varepsilon_k \dot{k} + \Sigma \eta_i \dot{z}_i + \Sigma D_i \dot{x}_i + \dot{T} . \tag{A.6}$$

The discrepancy between total cost expenditure shares in equation A.1 and variable cost expenditure shares in equation A.5 can be remedied by recognizing that $M_i = (1-M_K)\, M_i^v$. Combining equation A.3 with equation A.6 yields our total factor productivity growth decomposition

$$\begin{aligned} \dot{TFP} = {} & \Sigma\, [R_i - (1-M_k)\varepsilon_i]\dot{q}_i - [M_k + \varepsilon_k\, (1-M_k)]\, \dot{k} - \Sigma\, (1 - M_k)\eta_i \dot{z}_i \\ & - \Sigma\, (1 - M_k)\, D_i \dot{x}_i + (1-M_k)\, \dot{T} . \end{aligned} \tag{A.7}$$

The first term on the right describes the growth rate of total factor productivity due to increasing output. While these terms tend to be quite large, they are due to the low variable cost that is incurred when output is increased (essentially increasing load factor). The second term describes productivity growth due to growth in the capital stock. This also tends to be quite large and acts to dampen the productivity growth due to increasing output. Together, the first two terms can be viewed as growth in total factor productivity due to scale economies.

The third term describes the growth attributable to changing output characteristics. The fourth term describes the portion of TFP growth due to changes in the distorted variable input mix. Finally, the last term describes technological change.

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Table 1. Parameter Estimates and Standard Errors for Airline Variable Cost Functions

Input Use:	Efficient		Efficient		Efficient		Efficient		Distorted		Distorted		Distorted		Distorted	
Tech Chg:	Time Proxy		Time Proxy		Capital Attribute		Capital Attribute		Time Proxy		Time Proxy		Capital Attribute		Capital Attribute	
Estimator:	SUR		GMM		SUR		GMM		SUR		GMM		SUR		GMM	
parameter	**estim.**	**st.err**	**estim.**	**st.err**	**estim.**	**st.err**	**estim.**	**st.err**	**estim.**	**st.err**	**estim.**	**st.err**	**estim.**	**st.err**	**estim.**	**st.err**
β_K	0.48167	.00151	0.48185	.00151	0.48190	.00084	0.48194	.00085	0.24404	.06849	0.47534	.02360	0.45136	.01252	0.44643	.01236
β_E	0.27923	.00095	0.27913	.00096	0.27913	.00074	0.27910	.00075	0.54132	.12227	0.27904	.00483	0.27229	.00451	0.27455	.00386
$\beta_{L,L}$	0.17903	.02099	0.16665	.02255	0.12893	.01398	0.12353	.01462	0.04923	.02172	0.16746	.02712	0.14666	.01100	0.14124	.01319
$\beta_{L,E}$	-0.15989	.01029	-0.15407	.01224	-0.15051	.00596	-0.15133	.00640	-0.05572	.02154	-0.14659	.01443	-0.14531	.01198	-0.14060	.01163
$\beta_{E,E}$	0.20537	.00810	0.19680	.01106	0.19263	.00564	0.19368	.00623	0.11552	.04466	0.18990	.01780	0.22237	.01294	0.21513	.01322
α_0	19.12708	.04022	19.23835	.07572	19.23813	.04657	19.22551	.06818	18.82935	.17763	19.24424	.06548	19.23499	.04673	19.20560	.05716
α_{Q1}	0.39277	.02032	0.38730	.04167	0.37355	.01958	0.36085	.03128	0.45232	.03527	0.41407	.03610	0.38519	.01956	0.39062	.02622
α_{Q2}	0.04099	.01584	-0.01953	.02999	0.04247	.01491	0.03223	.02303	0.04123	.01636	-0.02621	.02572	0.04399	.01476	0.03014	.01899
$\alpha_{Q1,Q1}$	0.01446	.03668	0.06200	.07108	0.00370	.03562	-0.02534	.05320	-0.00817	.03591	0.07020	.06088	0.00664	.03515	-0.01340	.04350
$\alpha_{Q1,Q2}$	-0.05191	.03231	0.00177	.06426	-0.08059	.03146	-0.06149	.05289	-0.06488	.03090	-0.00069	.05566	-0.07883	.03107	-0.06707	.04312
$\alpha_{Q2,Q2}$	0.03219	.01336	0.01510	.02693	0.04935	.01344	0.03926	.02280	0.05432	.01390	0.01405	.02312	0.04912	.01341	0.04158	.01880
α_S	0.04983	.04290	-0.02425	.10336	-0.00135	.04707	-0.01268	.07769	0.06695	.04858	-0.04244	.08887	-0.00672	.04656	-0.01668	.06379
α_N	0.71690	.05755	0.63748	.14413	0.67962	.05653	0.71177	.10006	0.53316	.08754	0.63422	.12400	0.66029	.05568	0.66474	.08233
α_H	0.37559	.04379	0.30365	.11005	0.36511	.04032	0.40329	.07481	0.26026	.05426	0.29949	.09464	0.34786	.03993	0.36468	.06134
ρ_K	0.30171	.02567	0.39857	.05634	0.36446	.02634	0.36180	.04033	0.27329	.02841	0.38033	.04933	0.35509	.02610	0.33902	.03350
$\rho_{K,K}$	0.09801	.04700	0.24706	.09760	0.06370	.04453	0.03878	.06970	0.09168	.04553	0.25328	.08656	0.06611	.04421	0.04557	.05781
ρ_{A1}	---		---		-0.01767	.04156	0.04314	.06214	---		---		-0.01097	.04324	0.05060	.05418
ρ_{A2}	---		---		-0.40380	.07712	-0.34146	.12381	---		---		-0.39599	.07773	-0.31987	.10324
ρ_{A3}	---		---		0.26218	.18806	0.23054	.31762	---		---		0.24861	.18534	0.11724	.26137
ρ_{A4}	---		---		0.09205	.17258	0.36464	.35974	---		---		0.10349	.17014	0.38571	.29332
ρ_{A5}	---		---		0.26002	.17611	0.22325	.26238	---		---		0.26368	.17320	0.25615	.21505
α_T	-0.00222	.00093	-0.00363	.00179	---		---		-0.01063	.00136	-0.00336	.00157	---		---	
$\nu_{Q1,K}$	-0.02016	.07398	-0.24155	.15300	0.04682	.07073	0.06818	.10875	0.04692	.07485	-0.25341	.13260	0.03942	.06978	0.05457	.08901
$\nu_{Q2,K}$	-0.06419	.03237	-0.08155	.06078	-0.06996	.03267	-0.04452	.04927	-0.10980	.03254	-0.07818	.05406	-0.07192	.03238	-0.04950	.04054
Θ_L	---		---		---		---		-0.18922	.21547	-0.04257	.26695	-0.28883	.09644	-0.29142	.10090
Θ_E	---		---		---		---		14.07201	.09744	-0.10349	.11094	0.18318	.20306	0.02588	.13392
$\gamma_{L,Q1}$	-0.02509	.00898	-0.01828	.01017	-0.03161	.00557	-0.02808	.00617	-0.01514	.00555	-0.01530	.01060	-0.03211	.00531	-0.02751	.00615
$\gamma_{L,Q2}$	-0.00845	.00760	-0.00206	.00973	-0.02149	.00461	-0.02162	.00538	-0.00080	.00204	-0.00170	.00978	-0.02207	.00407	-0.02259	.00493
$\lambda_{L,K}$	0.03518	.01425	0.02120	.01827	0.04553	.00822	0.04478	.00941	0.00836	.00502	0.02069	.01859	0.04484	.00791	0.04520	.00902
$\gamma_{L,S}$	-0.02031	.01284	-0.02891	.01490	0.02267	.00940	0.02906	.01045	0.00242	.00361	-0.03299	.01559	0.01772	.00922	0.02128	.01067
$\gamma_{L,N}$	0.03159	.02020	0.03735	.02282	0.02597	.01344	0.02720	.01468	0.02305	.00972	0.03193	.02430	0.02517	.01315	0.02427	.01475
$\gamma_{L,H}$	0.01315	.01104	0.01512	.01224	0.03763	.00693	0.03732	.00746	0.00930	.00456	0.01293	.01287	0.03452	.00672	0.03379	.00741

Table 1. Parameter Estimates and Standard Errors for Airline Variable Cost Functions (continued)

Input Use:	Efficient		Efficient		Efficient		Efficient		Distorted		Distorted		Distorted		Distorted	
Tech Chg:	Time Proxy		Time Proxy		Capital Attribute		Capital Attribute		Time Proxy		Time Proxy		Capital Attribute		Capital Attribute	
Estimator:	SUR		GMM		SUR		GMM		SUR		GMM		SUR		GMM	
parameter	estim.	st.err	estim.	st.err	estim.	st.err	estim.	st.err	estim.	st.err	estim.	st.err	estim.	st.err	estim.	st.err
$\lambda_{L,A1}$	---		---		0.01785	.01394	0.01157	.01516	---		---		0.04493	.01519	0.04330	.01808
$\lambda_{L,A2}$	---		---		-0.07410	.01024	-0.07859	.01072	---		---		-0.05605	.01220	-0.06139	.01279
$\lambda_{L,A3}$	---		---		-0.39261	.03208	-0.37267	.03477	---		---		-0.37074	.03465	-0.35965	.03546
$\lambda_{L,A4}$	---		---		-0.33490	.02742	-0.37616	.02946	---		---		-0.30895	.03180	-0.36475	.03317
$\lambda_{L,A5}$	---		---		0.28090	.04196	0.24372	.04541	---		---		0.27338	.04177	0.25553	.04452
$\lambda_{L,T}$	0.00124	.00056	0.00131	.00066	---		---		0.00083	.00035	0.00154	.00094	---		---	
$\gamma_{E,Q1}$	0.04055	.00567	0.04132	.00658	0.04174	.00484	0.04597	.00534	0.02506	.01084	0.03818	.00817	0.04780	.00620	0.05001	.00682
$\gamma_{E,Q2}$	0.00764	.00478	0.00080	.00632	0.02383	.00405	0.02429	.00476	0.00080	.00257	0.00049	.00601	0.02549	.00486	0.02496	.00550
$\lambda_{E,K}$	-0.00497	.00915	0.00831	.01223	-0.01128	.00734	-0.00930	.00848	-0.00354	.00513	0.01023	.01200	-0.01120	.00878	-0.00772	.00967
$\gamma_{E,S}$	-0.04016	.00798	-0.04171	.00939	-0.04713	.00800	-0.05323	.00882	-0.01948	.01042	-0.03999	.01124	-0.04955	.00992	-0.05498	.01048
$\gamma_{E,N}$	-0.08969	.01273	-0.11039	.01463	-0.08410	.01163	-0.09824	.01271	-0.04712	.02074	-0.10632	.01655	-0.09227	.01443	-0.10537	.01516
$\gamma_{E,H}$	-0.03984	.00694	-0.04964	.00782	-0.05192	.00601	-0.05984	.00647	-0.02037	.00933	-0.04800	.00842	-0.05539	.00755	-0.06231	.00786
$\lambda_{E,A1}$	---		---		-0.05910	.01226	-0.06106	.01332	---		---		-0.08128	.01695	-0.07697	.01718
$\lambda_{E,A2}$	---		---		-0.01403	.00912	-0.01496	.00960	---		---		-0.02744	.01176	-0.02703	.01188
$\lambda_{E,A3}$	---		---		0.21542	.02821	0.23294	.03061	---		---		0.22919	.03821	0.23237	.03956
$\lambda_{E,A4}$	---		---		0.13525	.02422	0.14446	.02608	---		---		0.11629	.03065	0.12057	.03206
$\lambda_{E,A5}$	---		---		-0.13643	.03694	-0.16058	.04001	---		---		-0.12595	.04669	-0.14786	.04796
$\lambda_{E,T}$	-0.00191	.00039	-0.00178	.00051	---		---		-0.00104	.00068	-0.00179	.00051	---		---	
δ_{SPRING}	0.00014	.00578	-0.02948	.00781	0.00364	.00550	-0.03355	.00698	-0.00139	.00545	-0.00062	.00669	0.00241	.00542	0.00519	.00568
δ_{SUMMER}	-0.02694	.00579	-0.03035	.00819	-0.02542	.00546	-0.03064	.00706	-0.02669	.00547	-0.03014	.00702	-0.02646	.00538	-0.02752	.00577
δ_{FALL}	-0.02527	.00603	-0.00151	.00909	-0.02381	.00568	-0.00812	.00757	-0.02572	.00568	-0.03149	.00779	-0.02495	.00560	-0.02571	.00616
δ_{AL}	-0.10501	.05527	-0.25374	.10214	-0.38209	.07804	-0.36250	.12274	-0.08061	.05358	-0.26768	.08803	-0.37424	.07785	-0.32704	.10196
δ_{BN}	-0.09284	.03107	-0.18947	.06052	-0.13486	.03694	-0.13065	.05508	-0.13253	.02967	-0.18976	.05198	-0.14233	.03646	-0.13676	.04531
δ_{CO}	-0.03237	.03696	-0.06765	.08037	0.01744	.03825	0.05828	.05725	-0.08867	.03538	-0.06736	.06914	0.00792	.03766	0.03869	.04683
δ_{DL}	-0.07987	.03303	-0.15541	.06966	-0.08826	.03626	-0.05092	.06077	-0.05234	.03382	-0.17370	.05979	-0.09128	.03577	-0.05170	.04958
δ_{EA}	-0.08909	.03181	-0.14936	.06376	-0.14542	.03105	-0.12327	.04740	-0.06314	.03247	-0.16576	.05466	-0.14608	.03075	-0.12310	.03887
δ_{FL}	-0.27319	.05808	-0.42909	.10580	-0.49984	.07334	-0.48998	.10984	-0.29212	.05538	-0.45208	.09087	-0.49931	.07277	-0.48205	.09087
δ_{NC}	-0.17506	.06457	-0.38672	.13668	-0.43625	.07897	-0.39896	.12103	-0.16373	.06227	-0.40518	.11814	-0.43456	.07856	-0.38421	.10054
δ_{OZ}	-0.12991	.05362	-0.25225	.08758	-0.39613	.07768	-0.39008	.12006	-0.13435	.05205	-0.26561	.07528	-0.38693	.07764	-0.35288	.10029
δ_{PI}	-0.15625	.06193	-0.29140	.09911	-0.37716	.07500	-0.39785	.11696	-0.14929	.06024	-0.31129	.08497	-0.36889	.07493	-0.36247	.09739
δ_{TI}	-0.06135	.05483	-0.18163	.10881	-0.32900	.08289	-0.30855	.12773	-0.13273	.05271	-0.20756	.09324	-0.33169	.08293	-0.30118	.10676
δ_{UA}	-0.12988	.01742	-0.12676	.03789	-0.12575	.01938	-0.11136	.03592	-0.10716	.01752	-0.13319	.03251	-0.12262	.01917	-0.10560	.02940
δ_{WA}	-0.07707	.03443	-0.12990	.07066	-0.05805	.03542	-0.03325	.05137	-0.11198	.03237	-0.13547	.06088	-0.06597	.03498	-0.04945	.04218

Table 2. Derived Properties of Airline Variable Cost Functions

Input Use:	Efficient	Efficient	Efficient	Efficient	Distorted	Distorted	Distorted	Distorted
Tech Chg:	Time Proxy	Time Proxy	Capital Attribute	Capital Attribute	Time Proxy	Time Proxy	Capital Attribute	Capital Attribute
Estimator:	SUR	GMM	SUR	GMM	SUR	GMM	SUR	GMM
parameter	estimate	estimate	estimate	estimate	estimate	estimate	estimate	estimate
Regularity failures:								
Input Concavity	134	127	115	117	149	128	94	118
Output Marg costs	53	142	57	54	85	180	37	43
Total obs failing	165	199	158	170	186	240	125	151
Endogeneity:								
Hausman test χ^2 (df)	224.9 (48)		325.9 (60)		***		95.0 (62)	
Allen Elasticities†:								
$\eta_{L,L}$	-.3044	-.4085	-.5199	-.5431	-3.8887	-.3511	-.6279	-.6207
$\eta_{L,E}$	-.1888	-.1067	-.1189	-.1250	.2210	-.1442	-.0858	-.0732
$\eta_{L,M}$	.8338	.9483	1.1874	1.2414	1.5943	.8268	.9941	.9868
$\eta_{E,E}$	.0528	-.0807	-.1102	-.0965	-.0002	-.0674	-.0506	-.0605
$\eta_{E,M}$	.6593	.6546	.6842	.6824	.7388	.6713	.5923	.6033
$\eta_{M,M}$	-2.0519	-2.2733	-2.8250	-2.9300	-3.5140	-1.9818	-1.6228	-1.6264
Returns to Scale:† §								
Short-Run	2.314 (.097)	2.748 (.247)	2.403 (.105)	2.545 (.174)	1.763 (.161)	2.607 (.191)	2.270 (.103)	2.174 (.129)
Network Density	1.614 (.061)	1.643 (.159)	1.531 (.069)	1.626 (.112)	1.299 (.104)	1.629 (.126)	1.541 (.066)	1.442 (.083)
Network Size	.900 (.034)	.860 (.090)	.872 (.040)	.863 (.069)	.966 (.034)	.936 (.073)	.890 (.038)	.888 (.056)
Cost Complementarity:†								
Scheduled/Nonscheduled	-3.12% (3.32)	1.27% (6.52)	-6.47% (3.29)	-4.99% (5.48)	-4.21% (3.27)	-1.14% (5.06)	-5.63% (3.33)	-5.36% (4.45)
Productivity Growth:*								
TFP growth (quarterly)	1.6900	1.8246	1.5153	1.4696	3.9076	1.7198	1.3772	1.2231
component due to								
Output growth	2.2972	2.2689	2.3534	2.3576	1.9947	2.2281	2.2775	2.2747
Capital growth	-.8741	-1.0150	-.9825	-.9667	-.8251	-.9796	-.9414	-.9084
Input distortion	---	---	---	---	1.0568	-.0678	-.1371	-.2234
Network change	-.0912	-.0145	-.0093	.0231	-.0299	-.0021	.0088	.0244
Tech change	.3581	.5852	.1537	.0556	1.7110	.5412	.1694	.0559
Inefficiency:†								
% cost of distortion	---	---	---	---	37.192	.020	.497	.601
% overuse of labor	---	---	---	---	172.125	1.120	7.528	8.646
% overuse of energy	---	---	---	---	-30.738	0.583	2.104	1.684
% overuse of material	---	---	---	---	-55.087	-2.745	-12.571	-13.337
Shadow price/Measured Price:†								
Capital	1.529	1.638	1.523	1.444	4.747	1.515	1.302	1.142

Notes: * averages over entire sample. † computed at sample average quantities and prices. § Standard errors in parentheses.

*** Hausman test failed to produce reasonable results because of the high standard errors on the parameter estimates of the SUR model.

Figure 1. A Comparison of Index Number and Cost Function Measurement of TFP Growth

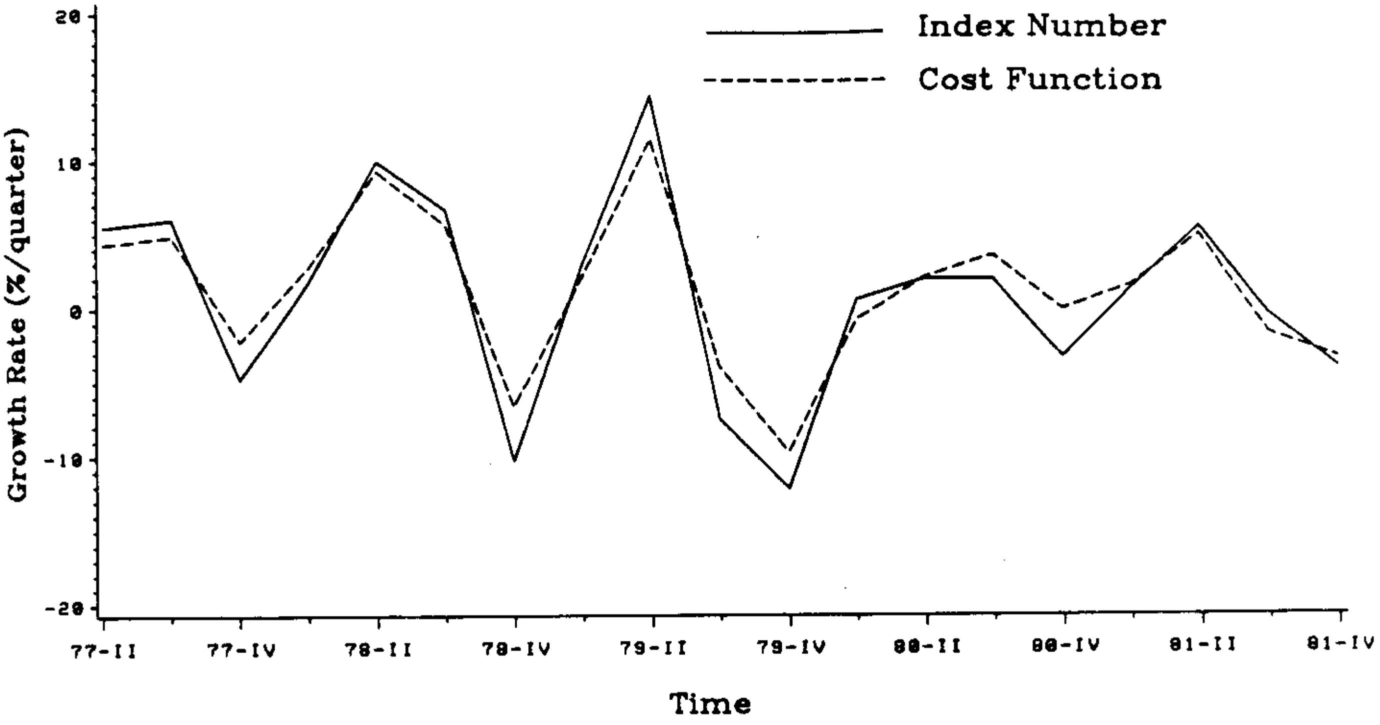

Figure 2. A Decomposition of Total Factor Productivity Growth

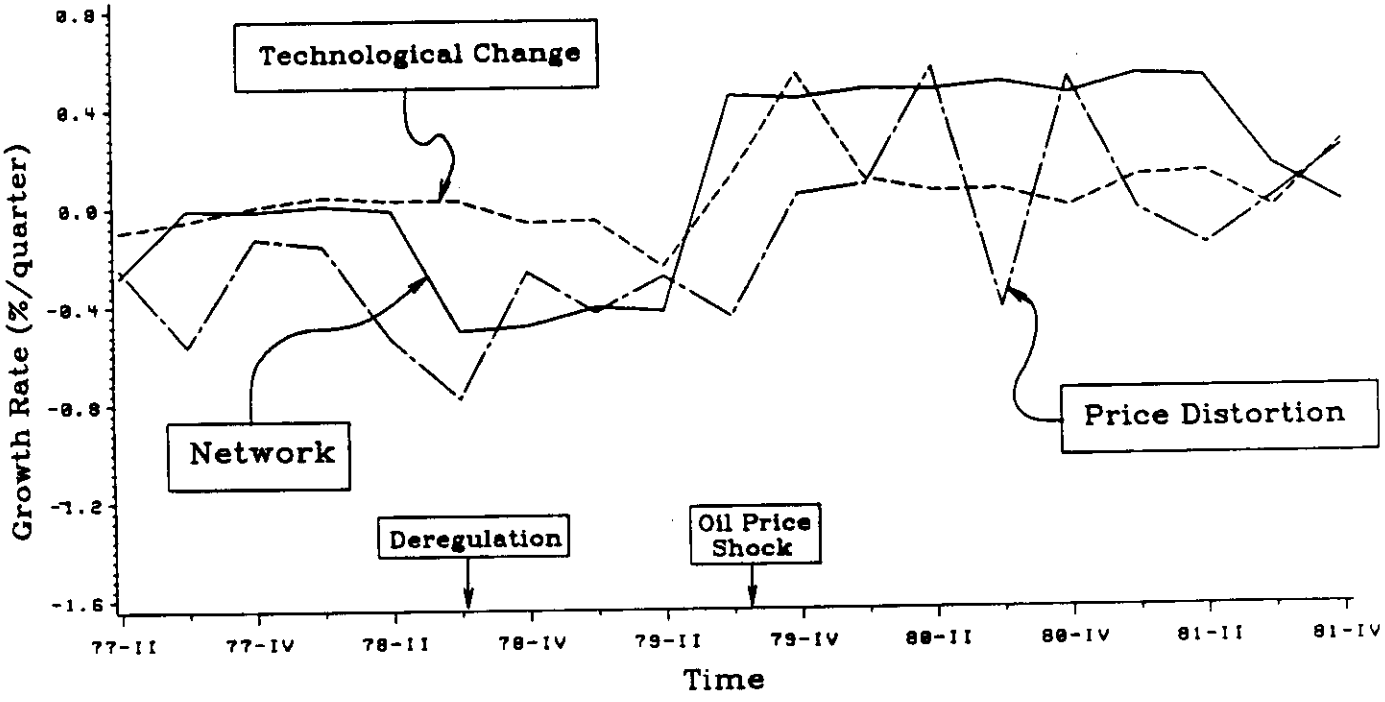

Figure 3a. Estimated Technological Change for Allocatively Inefficient Models

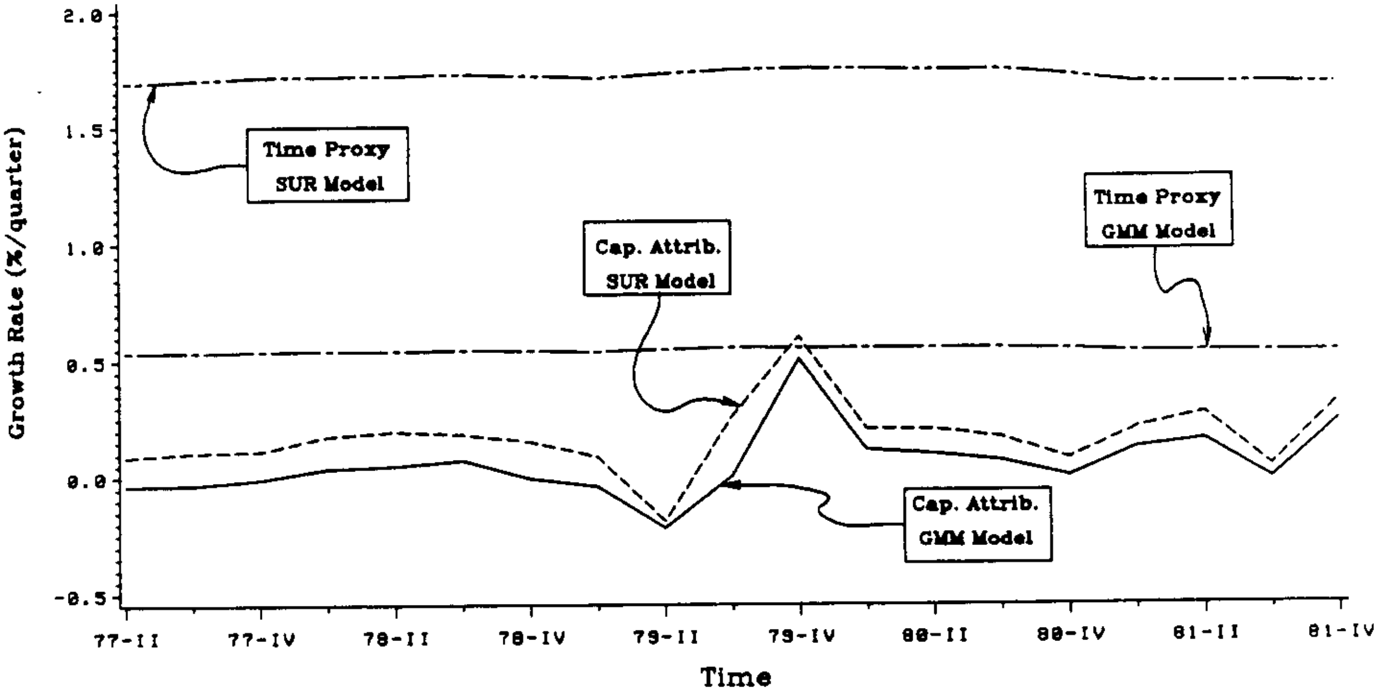

Figure 3b. Estimated Technological Change for Allocatively Efficient Models