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

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ABSTRACT

In this paper we construct a short run model of the firm describing the behavior of thirteen U.S. airlines during the difficult transition to deregulation. Several modeling scenarios are developed to assess three common assumptions in cost studies: the use of time as a proxy for technological change as opposed to a more thorough description of changes in the production technique, the assumption of cost minimizing behavior as opposed to permitting allocative inefficiency in input selection, and the assumption exogeneity of output and capital and their characteristics as opposed to endogenous decisions regarding these variables. Derived properties of the resulting eight combinations of these issues are calculated to identify the sensitivity of these properties to the modeling assumptions. The most dramatic finding is that input concavity are reduced by 80 percent by relaxing the assumption of cost minimization. Demand and substitution elasticities are nearly twice as large under our most flexible compared to the least flexible scenarios. Measured returns to scale are substantively much higher when a more complete description of the production technique is included in the model, and when this production technique is permitted to be modeled endogenously. Similarly, cost complementarity is quite sensitive to the assumption of endogeneity. Finally, cost models based on these three common assumptions over state the level of productivity growth by as much as 40%. By correctly modeling and estimating the production technique, our most general model predicts a level of productivity growth which is quite similar to that based on Divisia indices calculations.

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1. INTRODUCTION

Over the last three decades economists have expended substantial effort in formulating optimizing models which take account of the inherent complex-ities of technology.[1] In this paper we set out an integrated model that incorporates a wide range of these features of the production process in the U. S. airline industry. 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. We employ the concept of virtual prices in our modeling to allow estimation of a technology that corresponds to efficient resource allocation despite potentially noncost-minimizing behavior by the firms. An alternative interpretation of a divergence between virtual and observed prices is that there exist binding constraints on firm decision making and that the firm is in fact optimizing relative to those constraints. In the U. S. airline industry, specification of these constraints is problematic and empirical vehicles for modeling them have not been developed. However, to the extent that we can identify and estimate parameters that explain the divergence between virtual and observed prices, their role in explaining distortions in optimizing behavior is consistent with either of these interpretations. We explicitly formulate a multiple output technology in which the choice of production technique is an endogenous decision. Finally, rather than using time trends as proxies for disembodied technological change, we employ a variable cost function which explicitly incorporates characteristics of the embodied production technique. The models which we develop are used to examine the behavior of sixteen air

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[1] These innovations have included flexible functional forms (see Nadiri, 1982), models allowing multiple outputs (e.g., Hall, 1972; Brown, Caves and Christensen, 1979), the incorporation of characteristics of those outputs (e.g., Spady and Friedlaender, 1978), models of interrelated demand functions and temporary equilibria (e.g., Nadiri and Rosen, 1969; Pindyck and Rotemberg, 1982; Berndt and Morrison, 1981), and models allowing noncost-minimizing behavior (e.g., Lovell and Sickles, 1983; Atkinson and Halvorsen, 1984).

carriers between 1977 and 1983. During this period fuel prices changed dramatically and the commercial air transport industry was formally deregulated.

The paper is organized as follows: In section 2 we provide the institutional motivation for our generalization of the standard multiple output variable cost model. Next, in section 3, we detail the implication of distorted cost-minimizing behavior on the empirical specification of technology. Divergence between virtual prices and observed prices and hence between observed cost and shares and virtual cost and shares is parameterized using a translog variable cost function. Our model also extends previous work in that the array of technologies adopted by the firm as well as decisions regarding provision of service are allowed to be choice variables. The flexible production process has arguments which include two measured outputs (scheduled passenger and other revenue service), four output characteristics (average stage length, number of cities served, a measure of connectedness of the network, and load factor), three measured variable inputs (labor, energy, and materials), one measured fixed input (capital), and four characteristics of technology (average age of the fleet, percentage of jet powered aircraft, average aircraft size, and the diversity of sizes within the fleet).

Section 4 describes our cross-sectional time-series data on airlines for the period 1977 I-1983 IV. Section 5 outlines the strategy for estimating the distorted cost and share system and discusses estimation results. They indicate that the restrictions imposed on our general model by standard treatments of technical change and exogeneity and by the widely-used assumption of unconstrained cost-minimization are inconsistent with the data. Moreover, due to the failure of regularity conditions for the more restrictive specifications, it appears that our general model is the only specification capable of identifying the structure of airline service technology from the variable cost function. Section 6 provides concluding remarks.

2. THE INSTITUTIONAL ENVIRONMENT

In 1938, the Civil Aeronautics Board (CAB) was given the, often contradictory, mandates of maintaining the financial viability of the industry by providing air carriers with protection from competition while maintaining an efficiently operating air transport system by increasing the number of competitors. There is considerable evidence that the CAB's actions led to significant distortions in the production decisions of airlines.[2] In an attempt to protect carriers from competition fares, route entry and exit were strictly regulated, while the level of service and the choice of technology were not. This gave carriers the incentive to compete along service dimensions by offering flights too frequently and with too many amenities (space, food, etc.). Between 1945 and 1955 five new classes of airlines were introduced, each with its own mission. Trunk airlines, certificated in 1938, provided most long-haul service. Our study also includes local service airlines which were created to serve short-haul, low-density markets.

In addition to service competition, the nature of CAB regulation had implications for the firm's input decisions. Much of the principal agency literature suggests that the CAB's protection allowed managers to use their discretion to pursue nonprofit-maximizing objectives. In particular, expense preference theory suggests that managers hired excess employees.[3]

Kahn (1971) also describes how the technological change which occurred during the 1960s and early 1970s interacted with collective bargaining practices to encourage a distorted use of labor. Not all innovations led to cost reductions. Flight crew salaries for new equipment were based on the salaries

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[2] See Eads (1974), Phillips (1972) and Bailey, Graham and Kaplan (1985), Meyer and Oster (1981,1984).

[3] Williamson (1963) notes that managers could gain the approximate equivalent of promotion by hiring more workers. This behavior also encompasses "feather bedding," "empire building" or "satisficing." It is discussed in more detail for airlines in Good (1987).

that would have been earned using the less productive older equipment. This meant that benefits from the increased speed of jet equipment were 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 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 during the 1970s led to the gradual elimination of engineers (leaving a two person flight crew) on most small jets. Together with expense preference behavior, this suggests a systematic overuse of labor for all airlines.

Because of its multitiered regulatory system, the CAB's policies also affected airlines differentially during the study period. When the distinctions among carrier classes were eliminated by deregulation, different classes of carriers were, quite naturally, left with different types of aircraft fleets which were purchased to serve their different missions. Casual observation indicates that the former local service airlines were much more profitable during the transition than the former trunks. Furthermore, 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 (Eads, 1974), they were ideal for the newly deregulated environment (Meyer and Oster, 1981). 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 less appropriate for the deregulated environment since much of the new entry was manifested on high density routes.

Our study period follows the industry between 1977 and 1983. This is a particularly interesting period for our purposes since it includes both the difficult transition to deregulation as well as a nearly four-fold increase in fuel prices. Both of these are likely to induce a change in the level and mix of output produced and/or a change in the chosen production technique. New route entry and exit authority led to network modifications. Fuel price increases encouraged the retirement of older airplanes in favor of more fuel efficient aircraft types. Protection from competition on long-haul high density routes provided trunk airlines with incentives to invest in large wide-bodied jets. Subsidies provided to the local service carriers gave them incentives to invest in jet equipment that was not necessarily tailored to their short-haul routes after subsidies were lifted. Thus, some carriers entered the regulatory transition with fleet configurations which had been encouraged by prior regulatory incentives and were not necessarily well suited to airline markets after deregulation. Consequently, carriers modified their fleet configurations and hence their production techniques to meet the less restrictive regulatory environment.

3. THE MODEL

We deal with this complex set of constraints and incentives which were distortionary relative to the deregulated environment in the following fashion. We generalize the standard specification of technology by allowing the firm to operate at the wrong point on the boundary of its unconstrained production possibility set, given the output and input prices it faces and the behavioral objective of unconstrained cost minimization.[4] Consequently, the

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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 in which inefficiency is time

assumption of unconstrained cost minimization is a testable hypothesis rather than an *a priori* conjecture. Our model allows us to estimate parametrically the divergence between virtual and observed prices, <u>on average</u>, during the sample period by respecifying the standard observed cost and variable input factor share equations. This permits us to calculate the extent to which observed variable input allocations were at variance with virtual unconstrained cost-minimizing allocations. Quasi-fixed factor and output shares equations are not used in estimation, and thus distortions in observed output and fixed factor allocations can be examined by comparing these levels to their virtual cost minimizing levels after estimation. Our motivation for choosing this treatment for the sources of distortion stems in part from our wish to distinguish between systematic and nonsystematic impacts of regulation. In particular, CAB regulation appears to have 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 the capital stock that was employed.

We introduce distorted cost-minimizing behavior into our model in the following way. Consider the transformation function $F(Y,X) \leq 0$ characterized by the technology set. Airlines are assumed to employ inputs $X=(X_J,X_{N-J}) > 0$ to produce outputs $Y=(Y_K,Y_{M-K})$, where the last N-J inputs are assumed to be fixed (e.g., aircraft fleets) and where the last M-K elements of Y are output characteristics (e.g., service quality, network configurations, etc.). Consider a virtual technology and virtual input and output decisions that are consistent with the standard assumptions of duality theory, in particular with the assumption that the firm is an unconstrained cost minimizer. Label these functions and variables with a '*'. Next let virtual prices diverge from

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varying. For a stochastic frontier approach to modeling time varying inefficiency see Cornwell, Schmidt and Sickles (1990).

observed prices by an amount given by the parameter vector $\theta = (\theta_1, \dots, \theta_N)$. The cost-minimizing conditions in terms of the virtual (shadow) prices of input pair i,j are thus modified to be

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

Based on Shephard's lemma, factor demands derived from the firm's minimum virtual cost function are

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

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

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

and

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

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

$$C = C^*[\sum_i (M_i^* w_i/w_i^*)] \tag{3.4}$$

and observed factor shares can be re-expressed as

$$M_i = (M_i^* w_i/w_i^*)/\sum_j (M_j^* w_j/w_j^*)\ . \tag{3.5}$$

Equations (3.4) and (3.5) provide the key linkages between an observable cost function and the virtual technology when the application of that technology is systematically distorted.

The empirical vehicle for examining distortions in input allocations described by (3.4) and (3.5) 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

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

$$+ \tfrac{1}{2} \sum_n \sum_o \upsilon_{no} \ln y_n \ln x_{J+o-1} + \sum_i \beta_i \ln(w_i+\theta_i) + \tfrac{1}{2} \sum_p \sum_q \beta_{pq} \ln(w_p+\theta_p) \ln(w_q+\theta_q)$$

$$+ \tfrac{1}{2} \sum_r \sum_s \lambda_{rs} \ln(w_r+\theta_r) \ln x_{J+s-1} + \sum_i \rho_i \ln x_{J+i-1} + \tfrac{1}{2} \sum_t \sum_u \rho_{tu} \ln x_{J+t-1} \ln x_{J+u-1},$$

Virtual cost shares are given by

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

The relationship between the observed cost and share system and those of the virtual technology are given by

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

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

Symmetry and linear homogeneity in input prices are imposed on the virtual cost function by the restrictions $\alpha_{ij} = \alpha_{ji}$, $\forall i,j$; $\beta_{ij} = \beta_{ji}$, $\forall i,j$; $\sum_i \beta_i = 1$, $\sum_j \beta_{ij} = 0$, $\sum_j \lambda_{ij} = 0$, $\forall i$, and $\sum_j \gamma_{ij} = 0, \forall i$.

Summary statistics based on the virtual translog and its associated share equations are provided by the Morishima and Allen-Uzawa[5] substitution elasticities, and several measures of returns to scale which extend from the short-run to the long-run. A measure of excess costs due to the divergence of virtual and measured prices is given by the difference between the estimated

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[5] See Blackorby and Russell (1989) for a discussion of the relative merits of the Morishima and Allen-Uzawa elasticities.

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 when the virtual cost function is concave.

We allow for output and its characteristics and capital and its characteristics to be choice variables and thus for purposes of estimation, they are endogenous. The endogeneity of technology 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 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.

This menu of production techniques is modeled with a set of attributes of the aircraft fleet, and the effects of changes in these attributes over time is examined (see Baltagi and Griffin, 1988 for an alternative panel data treatment of technological change). We consider four attributes of the capital stock (vintage age, size, diversity in size, and percentage of the fleet that is jet powered) with the following rationale. 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, transportation industries tend to be 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 diseconomies. As equipment size increases it becomes more difficult to fine tune capacity on a particular route. Also, as capacity is concentrated into fewer departures, quality of service declines (the probability that a flight is offered at the time 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. On the other hand, through more vigorous fare competition, deregulation has increased the total volume of traffic, attenuating this liability to some degree. In any event, the operating economies of increased equipment size must be traded off for this limited flexibility.

Fleet diversity also represents tradeoffs. On the one hand, having different sizes of aircraft allows a 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 crew training costs as well as maintenance and the inventory of spare parts.

One of the most significant contributions to productivity growth in the 1960's was the introduction of jet equipment. While this innovation was widely adopted, it was not 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); one quasi-fixed input: flight and ground equipment; and four attributes of airline networks: the stage length, the number of cities serviced, the extent of network connectivity, and the load factor. Stage length allows us to account for differing ratios of costs 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 longer flights for a passenger-mile of output. Also, short flights tend to be more circuitously routed by air traffic control and spend a lower fraction of time at an efficient altitude than longer flights. 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. We provide further detail about output by including a variable to describe the extent of network connectedness. This allows us to control for airlines' decisions to make increased use of hub-and-spoke and loop type networks. These innovations allow carriers to reduce the number of flights while keeping passenger miles high, but they may artificially inflate the level of real production by increasing the air miles between cities and by reducing the likelihood of non-stop service. Our final output characteristic is load factor. Although this variable also can be viewed as a control for capacity utilization and macroeconomic demand shocks, it has been interpreted in many transportation studies as a proxy for service quality. As load factors increase, the number and length of flight delays increase as do the number of lost bags and ticketed passengers who are bumped. Inflight service also declines since the number of flight attendants is not adjusted upwards as load factors increase.

4. DATA

The data follow sixteen domestic air carriers with quarterly observations between 1977 and the end of 1983. These firms are the set of former certificated carriers that existed throughout the study period and accounts for well over 95 percent of the domestic air traffic. There are three notable exceptions. Pan American was excluded because virtually all of their traffic prior to 1979 was 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. Finally, reporting for Hughes Air West appeared to be very nonsystematic. Where mergers of these carriers occured, the pre and post merger entities were treated as separate firms. The remaining airlines are American, Allegheny (U.S. Air), Braniff, Continental, Delta, Eastern, Frontier, North Central, Ozark, Piedmont, Republic, Southern, Texas International, Trans World, 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 four broad input and two broad output indices using a Tornquist-Thiel multilateral index number procedure. The input indices are capital (K, the majority of which is aircraft, but also including ground equipment and landing fees), labor (L, an aggregate of pilot, flight attendant, mechanics, passenger and aircraft handlers, and other labor), energy (E, aircraft fuel) and a residual designated materials (M, which includes advertising, supplies, outside services, passenger food, maintenance materials, etc.). The output indices are scheduled revenue passenger output (Q1, an aggregate of first class and coach service) and other nonscheduled revenue services (Q2, including mail, cargo, and charter revenue operations). A detailed discussion of this data is contained in previous work (Sickles, et. al., 1986).

We add to this data on the network structure and capital characteristics. Stage length (S), describes the average length of route segments. The number of cities serviced (CTY), was taken from the Official Airline Guide. Our measure of network connectedness (HUB), also taken from the Official Airline Guide, divides the total number of route segments by the maximum possible number of routes for those cities served, N(N-1). Finally, load factor (LDF) describes the ratio of seat miles sold to those that were produced.

Data on technological characteristics were collected for individual aircraft types from Jane's (1945 - 1984 editions). The number of these different aircraft types in each airline fleet was collected from the CAB Form-41 Schedule T-2. We use the average number of months since FAA type certification of aircraft designs as our measure of fleet vintage (AGE). Our assumption 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 fully 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.[6]

Average equipment size (SIZ) was measured with the highest density seating configuration listed in Jane's for each aircraft type. This average across 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.[7] The diversity of equipment sizes (DIV) was constructed with the Gini coefficient. The higher the value of our measure, the lower the diversity of equipment sizes. Finally, it is clear that the major innovations which took place during the 1960's and 1970's was the conversion to jet aircraft. While many

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[6] Our assumption about freezing the technology embodied in an aircraft design is not a strong one. Modifications do occur along the production run of a design. Some of these modifications increase weight (redesign of parts that frequently breakdown) and some reduce weight (overdesigned components) occurs throughout the production run. These modifications rarely change the performance or mission of a particular aircraft type significantly. Major modifications, such as redesign of the DC 9-10 wing, bring along with them new type certification (as the DC 9-15). Turboprop equipment, such as the Convair 340 also experienced significant retrofitting and recertification.

[7] This definition caused minor 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). Maximum takeoff weight or volume provides an alternative measure of size which would avoid this difficulty. However, much of the volume or weight is unusable for passenger traffic, particularly with wide-bodied aircraft.

carriers had largely adopted this innovation prior to the study period, it was by no means universal. Many of the local service airlines had a significant portion of their fleet in turboprop aircraft. We implement this aspect of the chosen fleet by measuring the percent of aircraft which are jet powered (JET).

Since a major purpose of our analysis is to provide a model of endogenous production technique, we have also constructed price indices for five different aircraft categories to be used as instruments.[8] These five aircraft groups are very distinct in their characteristics and mission. Thus, they provide an alternative to our capital characteristics in describing production technique, though they do so somewhat less sharply. Further, because of their distinct missions, the aircraft groups are useful in describing the type of output that a carrier chose to produce. Carriers can be considered as price takers for these equipment types since aircraft are traded frequently and freely in international markets.

5. ESTIMATION, SPECIFICATION AND RESULTS

We first 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, four technology characteristics, two measured output quantities, and four output service characteristics. We control for cost neutral seasonal variations by including three seasonal dummy variables in the cost equation. A second order translog approximation to the cost function (3.6) would have

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[8] These additional price indices are annual lease prices for turboprop (CV440-CV640, YS-11, DH6, Nord 262), 2 engine narrow-bodied aircraft (DC-9, B-737, BAC-111), three engine narrow-bodied aircraft (B-727-200 and B-727-100), four engine narrow-bodied aircraft (B-707, DC-8, CV-880) and wide-bodied aircraft (DC-10, B-747, L-1011). The prices are based on those used in Caves, et al. (1984) and have been interpolated into quarterly data with the aid of Avmark information on current asset values for each aircraft type. Implicit price indices were constructed from the multilateral Divisia quantity indices for each aircraft category.

110 free parameters. With only 389 observations a restricted form of (3.6) must be found. Our specification allows for second-order effects in all variables except attributes of service and technology. Thus $\rho_{tu}=0$, for $t=k$ and u=AGE, SIZE, DIV, JET and $\alpha_{ij}=0$, for i=Q1, Q2 and j = STL, CTY, HUB, LDF. Our restrictions do not affect the way that outputs, output characteristics, capital or its characteristics enter into the input share equations. Further, 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 or do not change appreciable during the sample period. We also control for fixed firm effects by including firm dummy variables in the cost equation. These firm effects can be given the reduced form interpretation of omitted variables that are specific to the firm and display little variability over the sample period of seven years, or can be given a more structural interpretation as time invariant technical inefficiencies from a stochastic frontier cost function (Schmidt and Sickles, 1984). However, it is not clear that the later structural interpretation does justice to the data given the results of Cornwell, Schmidt and Sickles (1990). We thus view the time invariant fixed effects as unobserved/unmeasured firm specific heterogeneity.

Our analysis focuses on three related modeling issues. The first is whether or not the assumption that virtual and observed prices are the same is supported in the airline industry during the deregulatory transition. The competing hypotheses are represented by comparing restricted models (where $\theta=0$) with their unrestricted counterparts.

The second issue deals with how technological progress should be specified. We consider two approaches: the commonly used time trend specification and our capital attribute specification. In our capital attribute model a menu of different production technologies are explicitly described. Technological change is captured by how the adopted production technique changes over time.

The third deals with endogeneity of output, its characteristics and the production technique. We consider two estimators: the commonly used iterated seemingly unrelated regression method, ITSUR (Zellner, 1962), and iterated three stage least squares, IT3SLS. We allow the outputs, output characteristics, quasi-fixed inputs and the production technique to be endogenous. The instruments are constructed from nine input prices, the time trend, interactions among the input prices and time, as well as seasonal and airline dummies. We construct the instruments so that they are homogeneous of degree zero in prices in order to preserve the linear homogeneity of the estimated virtual cost function. Consideration of the aforementioned three issues leads to eight different models whose features are summarized below.

Features of Competing Models

Model	Allocative Efficiency	Treatment of Technical Change	Estimator
I	Yes	Time Trend	ITSUR
II	Yes	Time Trend	IT3SLS
III	Yes	Capital Attributes	ITSUR
IV	Yes	Capital Attributes	IT3SLS
V	No	Time Trend	ITSUR
VI	No	Time Trend	IT3SLS
VII	No	Capital Attributes	ITSUR
VIII	No	Capital Attributes	IT3SLS

Parameter estimates for our most general model (Model VIII) are presented in Table 1.[9] Table 2 contains an exhaustive set of test results and summary

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[9] Several different starting values were in the estimation of Models V through VIII. All models converged set of estimates without incident.

statistics based on these estimates. For comparison, summary statistics for less general models are provided in Appendix 2.[10] These summary statistics include Morishima and Allen-Uzawa elasticities of substitution, demand elasticities, estimates of short-run returns to scale, returns to route density, network hubbing and network size,[11] the degree of cost complementarity between scheduled and nonscheduled service, and the excess cost due to allocative distortions and its sources. Table 2 also includes the results of a decomposition of total factor productivity growth.[12] Finally, we provide measures of model fit, number and sources of regularity failures, and χ^2 statistics for our tests of endogenous technique and level of service.

We begin our discussion of results with a striking empirical finding. Failure to jointly treat these three modeling issues adequately leads to severe problems with, and often a complete breakdown in, estimates of the structure of production in the airline industry. The assumption that firms were unconstrained cost-minimizers is soundly rejected at standard nominal significance levels (from tests on θ in Table 1). The specification of disembodied technical change proxied by a time trend leads to a complete

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[10] The corresponding parameter estimates for the less general models are available from the authors.

[11] Our short-run measure of returns to scale is defined to be the inverse ray elasticity of cost for scheduled passenger and cargo/nonscheduled revenue services. Returns to route density adjusts 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) and also holds the capital characteristics fixed. Our returns to hubbing measurement also allows the number of cities served to proportionately increase while the number of route segments are held fixed. Finally, our returns to network size is defined to consider the inverse cost elasticity of proportionate increases in outputs, capital, and the number of cities while holding our connectedness measure fixed. While these measures of returns to scale are inspired by Caves, Christensen and Tretheway's work, our estimates will not be directly comparable to theirs since we hold capital characteristics constant, have included two network measures, and use quarterly data.

[12] A detailed description of this total factor productivity decomposition is provided in Appendix 3.

Table 1. Parameter Estimates for the Most General Airline Cost Function (Model VIII)

Coeff.	Estim	St Err	Coeff.	Estim	St Err	Coeff.	Estim	St Err
β_L	0.4322	.0156	α_{JET}	0.4784	.1752	$\gamma_{E,AGE}$	-0.0986	.0147
β_E	0.3347	.0204				$\gamma_{E,SIZ}$	-0.0737	.0104
$\beta_{L,L}$	0.0910	.0169	θ_L	0.0602	.1371	$\gamma_{E,DIV}$	0.0480	.0273
$\beta_{L,E}$	-0.0988	.0104	θ_E	1.4227	.4464	$\gamma_{E,JET}$	0.1347	.0219
$\beta_{E,E}$	0.1669	.0141						
			$\gamma_{L,Q1}$	-0.0449	.0089	δ_{SPR}	-0.0012	.0053
α_0	19.5094	.0542	$\gamma_{L,Q2}$	-0.0119	.0044	δ_{SUM}	-0.0026	.0060
α_{Q1}	0.4753	.0381	$\gamma_{L,K}$	0.0696	.0106	δ_{FAL}	-0.0052	.0060
α_{Q2}	0.0956	.0211	$\gamma_{L,STL}$	-0.0234	.0106			
$\alpha_{Q1,Q1}$	0.2649	.1263	$\gamma_{L,CTY}$	-0.0344	.0190	δ_{AL}	-0.4091	.0806
$\alpha_{Q1,Q2}$	-0.0291	.0563	$\gamma_{L,HUB}$	-0.0095	.0092	δ_{BN}	-0.2743	.0483
$\alpha_{Q2,Q2}$	0.0313	.0480	$\gamma_{L,LDF}$	0.1122	.0153	δ_{CO}	-0.3207	.0405
ρ_K	0.0517	.0437	$\gamma_{L,AGE}$	0.0601	.0150	δ_{DL}	-0.0995	.0412
$\rho_{K,K}$	0.3469	.1535	$\gamma_{L,SIZ}$	0.0039	.0123	δ_{EA}	-0.0475	.0390
$\nu_{Q1,K}$	-0.2659	.1251	$\gamma_{L,DIV}$	-0.1680	.0302	δ_{FL}	-0.5361	.0802
$\nu_{Q2,K}$	-0.0317	.0545	$\gamma_{L,JET}$	-0.0557	.0255	δ_{NC}	-0.5989	.0781
						δ_{OZ}	-0.6434	.0784
α_{STL}	-0.0205	.0496	$\gamma_{E,Q1}$	0.1032	.0073	δ_{SO}	-0.7251	.0830
α_{CTY}	0.3136	.0667	$\gamma_{E,Q2}$	0.0293	.0040	δ_{PI}	-0.5095	.0851
α_{HUB}	0.2236	.0369	$\gamma_{E,K}$	-0.1044	.0100	δ_{TI}	-0.7431	.0839
α_{LDF}	-0.4076	.0615	$\gamma_{E,STL}$	-0.0435	.0092	δ_{TW}	-0.1268	.0286
α_{AGE}	0.0700	.0399	$\gamma_{E,CTY}$	-0.0238	.0165	δ_{RC}	-0.4025	.0818
α_{SIZ}	-0.2940	.0542	$\gamma_{E,HUB}$	-0.0056	.0082	δ_{UA}	-0.0374	.0189
α_{DIV}	-0.5199	.2590	$\gamma_{E,LDF}$	-0.1952	.0130	δ_{WA}	-0.3981	.0430

Subscripts:	L	ln(Labor price)	CTY	ln(No. of cities served)
	E	ln(Energy price)	HUB	ln(Network connectedness)
	M	ln(Materials price)	AGE	ln(Aircraft age)
	K	ln(Capital quantity)	SIZ	ln(Aircraft size)
	Q1	ln(Passenger output quantity)	DIV	ln(Diversity of size)
	Q2	ln(Nonsched output quantity)	JET	Percent of Jets
	STL	ln(Stage Length)	LDF	ln(Load Factor)
	AL, BN, CO, DL, EA, FL, NC, OZ, PI, TI, TW, RC, UA, WA		Airline dummy variables	
	SPR, SUM, FAL		Seasonal dummy variables	

breakdown of the model in that regularity conditions fail at almost all of the sample observations (see Appendix 1). Models I and V fail regularity at 93% of sample observations, while models II and VI fail for over 75% and 77% of the sample respectively. The exogeneity of technical change and service output decisions was rejected at nominal significance levels. Finally, Models I-VII yield negative shadow prices for capital. The only specification for which these joint problems are mitigated is the most general model, Model VIII. The average shadow price of capital services is positive in Model VIII,

Table 2. Summary Statistics for the Most General Airline Cost Function (Model VIII)

Regularity failures:	Input Concavity	0	
	Output Marg Costs	0	
	Capital Shadow Price	113	
	Total Observations Failing	113	
Model Fit (R^2):	Cost equation	.9986	
	Labor share equation	.8529	
	Energy share equation	.9449	
Hausman-Wu Endogeneity Test	χ^2	193.8	(65 df)
Morishima Elasticities:†§	$\eta_{L,E}$	.4619	(.0721)
	$\eta_{L,M}$	.6081	(.0560)
	$\eta_{E,L}$	.2951	(.0868)
	$\eta_{E,M}$	.1886	(.0738)
	$\eta_{M,L}$	.9818	(.1197)
	$\eta_{M,E}$	.5552	(.0990)
Allen-Uzawa Elasticities:†§	$\eta_{L,E}$	.3105	(.0906)
	$\eta_{L,M}$	1.0834	(.1171)
	$\eta_{E,M}$	.1228	(.1188)
Demand Elasticities:†§	ϵ_L	-.3567	(.0403)
	ϵ_E	-.1612	(.0521)
	ϵ_M	-.5123	(.0693)
Returns to Scale:†§	Short-Run	1.7666	(.1213)
	Network Density	1.6710	(.1095)
	Network Hubbing	1.4406	(.0853)
	Network Size	1.0744	(.0619)
Cost Complementarity:†§	Scheduled/Nonsched	1.4990	(5.641)
Productivity Growth:*# amount due to	Total TFP growth (%/qtr.)	1.258	
	Output mix	0.852	
	Output scale	0.941	
	Capital growth	-0.226	
	Network change	0.308	
	Tech change	0.042	
	Input Distortion	-0.659	
Allocative Distortion:	% allocative costs	2.58%	
	% overuse of labor	11.91%	
	% overuse of energy	-13.89%	
	% overuse of material	8.92%	
Ratio of Shadow to Observed Price*			
	Scheduled Pass Output	.7713	
	Other Output	2.1312	
	Capital	.4340	

Notes: * Averages over entire sample.
† Computed at sample average quantities and prices.
§ Standard errors in parentheses computed by simulation.
# Averaged measured value using Divisia indices is 1.203

although estimated shadow prices for the quasi-fixed capital stock are still negative for 31% of the sample observations. However, we are unaware of any other empirical study of U.S. airlines that has found a positive shadow price for capital for such a large portion of the sample observations. As a result of the comparative performances of Models I-VIII, we conclude that estimated properties of the technology based on models I-VII could be seriously misleading for policy makers. We therefore focus the remainder of our discussion of results on the summary statistics and empirical implications of our general model, Model VIII.

As we have said, the assumption of unconstrained cost-minimization is not supported by the airline data. Our results suggest that the airlines in our sample are over utilizing both labor and capital. Moreover, there is evidence of an underutilization of energy and overutilization of materials relative to levels consistent with unconstrained cost-minimization.

The figures in Table 2 compare the amount of labor used to the amount that would have been used if the firm had chosen an unconstrained cost minimizing input mix. For the most general model, labor and materials are overused by 12 and 9 percent respectively. Naturally, to stay on the same isoquant, fuel must be underused, in this case by approximately 14 percent. Even though labor and materials are overused, these inputs are still productive and are substituted for using less energy. Consequently, the 2.6% increase in cost due to the incorrect input mix is substantially less than the expenditures on the overused inputs. As stated previously, there are several reason why this result might hold. First, unions had been able to capture many of the productivity gains resulting from changes in technology, suggesting that work rules in addition to wage rates were bargaining objectives. For example, the change from three to two person flight crews on DC-9 and B-737 aircraft was slow to occur over the study period. Further, companies were reluctant to layoff workers during temporary periods of slack demand due to typical seasonal and macro business cycle fluctuations. This might also suggest that there were some quasi-fixed factor aspects to the labor input. Moreover, one often-cited outcome of the lack of price competition was excessive service competition, accomplished in part through such items as meal quality. Our results are suggestive of the patterns of relative resource mix changes that should have occurred during the sample period as airline firms adjusted to the less constrained deregulated environment. Our distortion estimates indicate that in order for firms to be unconstrained cost-minimizers, labor's share in total cost should have fallen during the sample period by 7.3 percent. The share of energy should have increased by 10.1 percent. The share of materials should have fallen by 7.2 percent. The share of capital should have fallen by about 4.5 percent. These figures are comparable to the 1977-83 sample changes of 5.3, 10.2, 0.3, and 3.2 percent. Whether or not the poor fit for materials is due to its "residual" input nature, or rather the strong substitution possibilities between labor and materials is unclear. However, in the absence of distortions, a fall in labor quantity of 11.91 percent could be brought about by a roughly 30% rise in the virtual price, given the short-run demand elasticity for labor of -0.357 (Table 2). This in itself would increase the quantity demanded of materials by no more than 30 percent since the cross elasticities are in the range of unity. This could certainly offset the downward adjustment in materials suggested by the divergence of the virtual and observed price supporting observed materials demand and may explain the small observed increase in materials share.

Short-run factor demands for all variable factors are inelastic, with energy (-0.088) the least elastic, followed by labor (-0.305) and materials (-0.466). The Morishima substitution elasticities for the labor/materials pair are [0.552,0.941] while the Allen-Uzawa elasticity is 1.006. Comparable estimates for the materials/energy and labor/energy pairs are [0.081,0.458] and -.036, and [0.362,0.184] and .203 respectively. These substitution possibilities are sensible and due, in part, to the ability of firms to substitute labor within the firm with outside labor services (predominantly contract maintenance and travel agent commissions) and to contract out for maintenance and spare parts. The substitution elasticities for the labor/energy pair are small and appear to be best characterized by fixed coefficients.

Short-run returns to scale are estimated to be 1.77. While on the surface this may seem high, it is due mainly to large fluctuations in demand coming from our quarterly data. Its primary effect is to capture increasing utilization rates of capital and labor over these seasonal fluctuations. The value of what Caves, Christensen and Tretheway term "returns to density" is estimated at 1.67. This measure assesses the change in cost as outputs are proportionately increased while holding the network, its characteristics, and the characteristics of the aircraft fleet fixed. While higher than the Caves, Christensen and Tretheway value of 1.24, it can again partially be explained by the use of quarterly data and a somewhat different study period. An alternative measure of scale economies examines the returns to additional cities added to the network with no new route segments. This type of output change can be accomplished only if additional use is made of sparser networks (such as by using hub-and-spoke or loop type networks). We term this returns to hubbing and estimated it at 1.44. Returns to size allows output, capital, the number of cities and the number of routes to increase proportionately and is estimated to be 1.07. Clearly, the way that airline networks have changed falls somewhere between the returns to hubbing and returns to size estimates, but their magnitudes suggest that the intensity of merger activity since deregulation may have resulted, in part, from some modest scale economies. It may also represent benefits from increases in feed traffic and the desire of consumers to complete their entire flight with the same carrier.

Our estimate of cost complementarity indicates that scheduled passenger output and cargo/nonscheduled output are very slight substitutes. While the belly of aircraft scheduled for passenger services can also hold cargo, the decline in popularity of combination aircraft since deregulation has meant that most cargo is carried by air freighters. Most carriers (Eastern, and U.S. Air are two exceptions) have substantially reduced charter operations since deregulation. Other former charter-only operators, such as Capitol, have not fared well in offering scheduled services. At the same time, carriers such as American Trans Air which did not enter the scheduled services market have been very profitable. Similar experiences can be observed for former all cargo carriers such as Federal Express and Flying Tiger. After brief experiences with offering scheduled passenger services, both returned to being cargo-only operations.

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

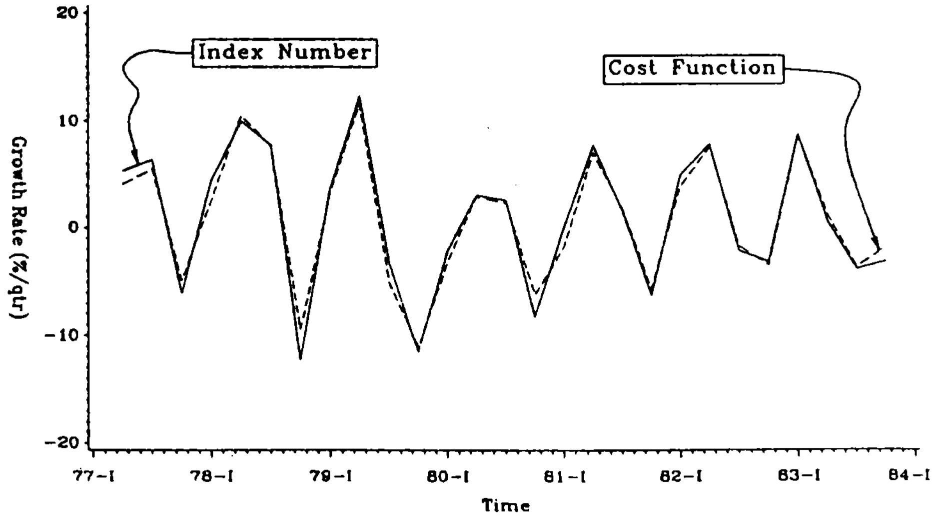


Figure 1 demonstrates the close correspondence of total factor productivity (TFP) growth estimates and TFP growth based on index number calculations. Figures 2a and 2b display the temporal decomposition of TFP growth described in Appendix 2. It provides additional insights into the process of growth. Seasonal fluctuations have been smoothed in Figure 2 using a 4-period moving average process. The decomposition demonstrates that an

Figure 2a. Decomposition of TFP Growth:
Output Scale, Mix, and Network Characteristics

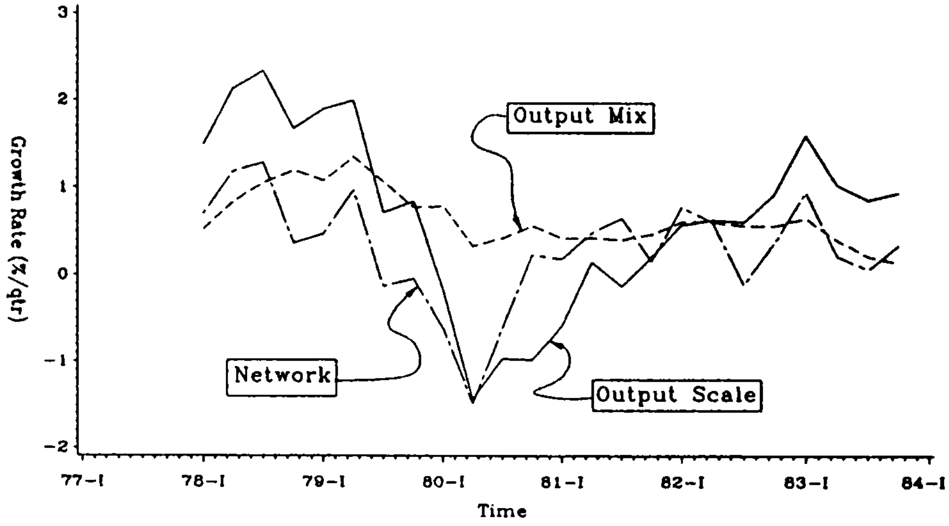
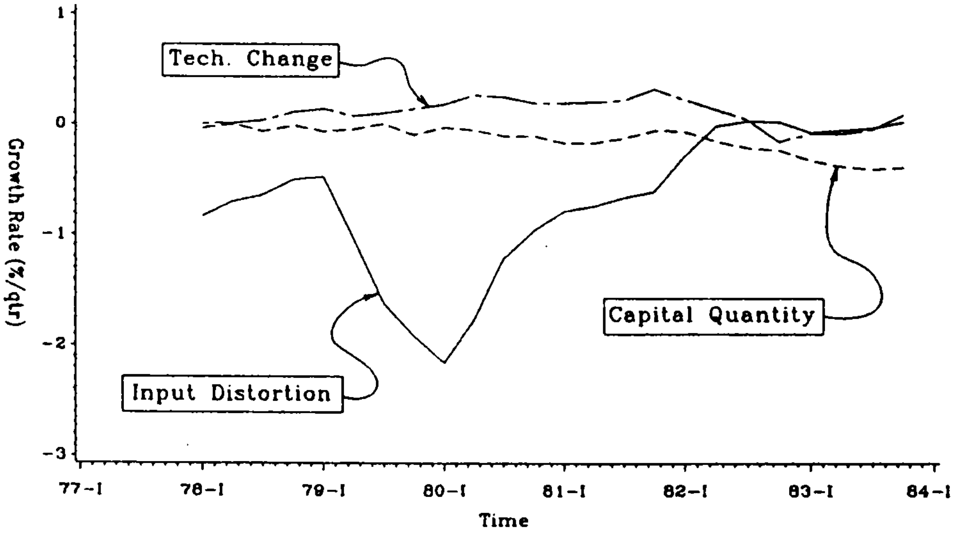


Figure 2b. Decomposition of TFP Growth:
Input Distortion, Capital, and Tech. Change



important contribution to total factor productivity growth has been a reduction in output mix departures from those consistent with marginal cost pricing, but that by 1984 the reduction in these distortions was largely played out. This is consistent with other work (Sickles, Good and Johnson, 1986). Economies of scale played an important role in TFP growth prior to deregulation and the period from 1982-1983, but provided significant negative contributions in the period from 1979 through 1981. Both output scale and output characteristics contributions to TFP growth seem to have been significantly affected for the worse by the 1979-1980 oil price shock. Input distortions were a significant drain on TFP growth prior to 1982. In fact, during the early deregulatory period, they slowed TFP growth by a full percentage per quarter. Changing the attributes of the capital stock led to a sizable productivity growth of approximately .15% per quarter with the exception of the recession period beginning in 1982 where little equipment replacement occurred.

6. 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 unconstrained cost minimized levels, and in which firms have a choice among a menu of embodied technologies and levels of service. The results suggest that our general specification describes the structure of technology, technological change, and the pattern of allocative distortions for the airline industry quite well using a wide variety of criteria over the difficult time period following the deregulation of the industry.

All of the characteristics of our model are statistically and substantively important. Exogeneity of output, capital and network characteristics was always rejected. This consistently led to fewer regularity violations, large impacts on the measurement of cost complementarity and returns to network size, and more elastic input demand schedules. Allowing for potential distortion in the use of variable inputs had large effects on the pattern of substitutability and in providing a specification of technology flexible enough to satisfy input concavity requirements. Specifying technology with the attributes of the embodied technique rather than using a time trend to proxy disembodied technical change led to significant changes in returns to network size and cost complementarity. Further, important properties of the underlying technology, cost complementarity, returns to scale, curvature, and productivity growth appear to be substantively affected by relaxing common assumptions about technology.

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Appendix 1: Derived Properties of Variable Cost Functions

Input Use: Tech Chg: Estimator:	Model I Efficient Time Proxy ITSUR	Model II Efficient Time Proxy IT3SLS	Model III Efficient Cap Attrib ITSUR	Model IV Efficient Cap Attrib IT3SLS	Model V Distorted Time Proxy ITSUR	Model VI Distorted Time Proxy IT3SLS	Model VII Distorted Cap Attrib ITSUR	Model VIII Distorted Cap Attrib IT3SLS
Regularity failures:								
Input Concavity	106	71	119	71	0	89	0	0
Output Marg Costs	19	23	91	0	42	37	81	0
Capital Shadow Price	361	262	361	347	361	265	358	113
Total Observations Failing	361	272	361	347	361	281	358	113
Hausman χ^2 test (df):	302.8(54)		204.8(63)		200.4(56)		193.8(65)	
Model Fit (R^2):								
Cost equation	.9975	.9973	.9981	.9983	.9979	.9974	.9984	.9986
Labor share equation	.7844	.7860	.8484	.8475	.7762	.7871	.8468	.8529
Energy share equation	.9150	.9165	.9442	.9454	.9103	.9168	.9426	.9449
Morishima Elasticities:[†§]								
$\eta_{L,E}$	.205 (.030)	.328 (.037)	.245 (.129)	.362 (.058)	.177 (.037)	.329 (.040)	.204 (.031)	.462 (.072)
$\eta_{L,M}$	.348 (.054)	.486 (.058)	.405 (.134)	.552 (.085)	.369 (.049)	.488 (.063)	.426 (.045)	.608 (.056)
$\eta_{E,L}$	.105 (.017)	.193 (.027)	.105 (.113)	.184 (.040)	.028 (.067)	.203 (.043)	-.016 (.040)	.295 (.087)
$\eta_{E,M}$	.105 (.021)	.101 (.023)	.068 (.025)	.081 (.025)	.083 (.093)	.115 (.042)	.001 (.047)	.189 (.074)
$\eta_{M,L}$	.666 (.107)	.829 (.109)	.737 (.159)	.941 (.146)	.811 (.210)	.886 (.201)	.854 (.120)	.982 (.120)
$\eta_{M,E}$	.393 (.066)	.420 (.065)	.387 (.070)	.458 (.080)	.503 (.194)	.460 (.123)	.439 (.089)	.555 (.099)
Allen-Uzawa Elasticities:[†§]								
$\eta_{L,E}$	.075 (.030)	.201 (.040)	.100 (.157)	.203 (.060)	-.018 (.052)	.202 (.044)	-.022 (.039)	.311 (.091)
$\eta_{L,M}$	.664 (.111)	.874 (.114)	.768 (.198)	1.006 (.159)	.795 (.144)	.908 (.167)	.900 (.104)	1.083 (.117)
$\eta_{E,M}$	.141 (.064)	.013 (.069)	.043 (.156)	-.031 (.090)	.214 (.210)	.042 (.091)	.025 (.097)	.123 (.119)
Input Demand Elasticities:[†§]								
ϵ_L	-.184 (.027)	-.271 (.031)	-.217 (.087)	-.305 (.047)	-.182 (.028)	-.210 (.024)	-.272 (.033)	-.357 (.040)
ϵ_E	-.070 (.009)	-.098 (.012)	-.058 (.040)	-.088 (.015)	-.037 (.052)	-.005 (.027)	.106 (.026)	-.161 (.052)
ϵ_M	-.355 (.057)	-.416 (.056)	-.374 (.070)	-.466 (.073)	-.438 (.134)	-.431 (.068)	-.449 (.107)	-.512 (.069)

Notes: [*] Averages over entire sample.

[†] Computed at sample average quantities and prices.

[§] Standard errors in parentheses computed by simulation.

[#] Averaged measured value using Divisia indices is 1.203

Appendix 1: Derived Properties of Variable Cost Functions (cont.)

Input Use: Tech Chg: Estimator:	Model I Efficient Time Proxy ITSUR	Model II Efficient Time Proxy IT3SLS	Model III Efficient Cap Attrib ITSUR	Model IV Efficient Cap Attrib IT3SLS	Model V Distorted Time Proxy ITSUR	Model VI Distorted Time Proxy IT3SLS	Model VII Distorted Cap Attrib ITSUR	Model VIII Distorted Cap Attrib IT3SLS
Returns to Scale:†§								
Short-Run	1.639 (.073)	1.682 (.137)	1.803 (.197)	1.992 (.470)	1.638 (.068)	1.660 (.137)	1.755 (.077)	1.767 (.121)
Network Density	1.495 (.050)	1.568 (.106)	1.479 (.145)	1.826 (.343)	1.494 (.047)	1.562 (.109)	1.491 (.057)	1.671 (.110)
Network Hubbing	.911 (.019)	1.016 (.046)	1.108 (.095)	1.497 (.241)	.923 (.019)	1.048 (.050)	1.125 (.033)	1.441 (.085)
Network Size	.725 (.019)	.792 (.035)	.877 (.088)	1.094 (.214)	.739 (.018)	.818 (.037)	.885 (.032)	1.074 (.062)
Cost Complementarity:†§								
Scheduled/Nonsched.	-8.35 (2.46)	20.55 (8.11)	-14.24 (7.31)	-1.81(10.34)	-6.74 (2.38)	22.99 (8.40)	-11.86 (2.31)	1.50 (5.64)
Productivity Growth:*#								
tot TFP growth (qtr.)	1.711	1.655	1.704	1.791	1.450	1.631	1.364	1.258
amt due to								
Output mix	0.809	0.682	0.804	0.848	0.759	0.649	0.820	0.852
Output scale	1.116	1.161	1.230	1.276	1.040	1.171	1.049	0.941
Capital growth	-0.360	-0.378	-0.517	-0.358	-0.359	-0.370	-0.450	-0.226
Network change	-0.207	-0.086	0.087	0.079	-0.079	-0.058	0.228	0.308
Tech change	0.355	0.276	0.102	-0.053	0.417	0.269	0.138	0.042
Input distortion	.000	.000	.000	.000	-0.326	-0.031	-0.422	-0.659
Allocative & technical inefficiency:								
% allocative costs	----	----	----	----	.44%	.01%	.36%	2.58%
% overuse of labor	----	----	----	----	1.85%	-1.25%	1.09%	11.91%
% overuse of energy	----	----	----	----	-4.16%	.59%	-2.79%	-13.89%
% overuse of material	----	----	----	----	3.36%	1.83%	2.71%	8.92%
Ratio of Shadow Price to Observed Price*								
Scheduled Pass. Output	.4967	.4639	.4753	.4160	.6294	.4827	.6481	.7713
Other Output	.9382	1.7308	.5353	1.1905	1.0363	1.6739	.9018	2.1312
Capital	-.5814	-.4597	-1.1862	-.4628	-.5771	-.4147	-.9060	.4340

Notes: * Averages over entire sample.

† Computed at sample average quantities and prices.

§ Standard errors in parentheses computed by simulation.

Averaged measured value using Divisia indices is 1.203

APPENDIX 2: 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

$$\text{(A.1)} \qquad \dot{TFP} = \Sigma\, R_i\dot{q}_i - \sum_{i\neq k} M_i\dot{x}_i - M_k\dot{k}$$

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, a set of output characteristics, z, and a set of capital characteristics, y, the observed variable cost function is

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

The growth rate of observed variable cost is

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

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 since the cost elasticity with respect to input prices is not necessarily the expenditure share due to potential allocative distortions. Since $C^v = \Sigma\, w_i\, x_i$, the growth rate of observed variable cost can also be described by $\dot{C}^v = \Sigma\, M_i^v\dot{w}_i + \Sigma\, M_i^v\dot{x}_i$. A bit of algebra reveals that

$$\text{(A.4)} \qquad \Sigma M_i^Y \dot{x}_i = \Sigma \varepsilon_i \dot{q}_i + \varepsilon_k \dot{k} + \Sigma \eta_i \dot{z}_i + \Sigma D_i \dot{w}_i + \dot{T}.$$

The discrepancy between total cost expenditure shares in equation A.1 and variable cost expenditure shares in equation A.4 can be remedied by recognizing that $M_i = (1-M_k)\, M_i^Y$. Combining equation A.3 with equation A.4 yields the following decomposition

$$\text{(A.5)} \qquad T\dot{F}P = \Sigma\, [R_i - (1-M_k)\varepsilon_i]\dot{q}_i - [M_k + \varepsilon_k\, (1-M_k)]\, \dot{k} - \Sigma\, (1-M_k)\eta_i \dot{z}_i$$
$$- (1-M_k)\, \Sigma\, [\frac{\alpha \ln c^v}{\alpha \ln w_i} - M_i^Y]\dot{w}_i - (1-M_k)\, \dot{T}.$$

The first term on the right can be further decomposed into a scale effect and a nonmarginal cost pricing effect:

$$\text{(A.6)} \qquad T\dot{F}P = \Sigma\, [R_j - \frac{\varepsilon_j}{\Sigma \varepsilon_k}]\, \dot{q}_j + [1-(1-M_k)\Sigma \varepsilon_i]\, \Sigma\, \frac{\varepsilon_j \dot{q}_j}{\Sigma \varepsilon_i} - [(1-M_k)\varepsilon_k + M_k]\, \dot{k}$$
$$- (1-M_k)\, \Sigma[\, \frac{\partial \ln C^v}{\partial \ln w_i} - M_i^Y]\, \dot{w}_i - (1-M_k)\, \Sigma\, \eta_i\, \dot{z}_i - (1-M_k)\dot{T}$$

The first term describes the component of TFP growth which can be attributed to nonmarginal cost pricing (output mix). The second term presents a multiple output component of TFP growth which is attributable to scale economies. The third term depicts productivity growth due to changing the quantity of the quasi-fixed factor, capital. The fourth term describes TFP growth which can be attributed to non-cost minimizing behavior. Note that when Shephard's lemma is applied, cost elasticities and input shares are identical and the term disappears. The fifth component describes TFP growth which is attributable to changing output and network characteristics. Finally, the last term describes the amount of technological change, that is, the rate of cost diminution attributable to shifts in the production technology.