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4 Energy Efficiency, User-Cost Change, and the Measurement of Durable Goods Prices

Robert J. Gordon

4.1 Introduction

4.1.1 User-Cost Changes and the Quality Change Debate

Energy price increases in the 1970s have induced producers to supply more energy-efficient automobiles, appliances, aircraft engines, and structures. Technological advances in response to higher labor costs have resulted in reduced maintenance requirements for many types of durable goods. Other changes in efficiency, particularly those associated with environmental legislation, have had an adverse effect on user cost. Users value the savings in energy consumption and repair costs that new, more efficient models make possible, just as they would pay to avoid a shift to less efficient models. Yet the literature on price measurement has concentrated on the dimensional or performance characteristics of goods and contains little explicit discussion of the procedures by which price changes should be measured when new models embody changes in operating costs.

In price measurement the proper treatment of changes in energy efficiency and other aspects of user cost is related to the more general problem of adjusting for quality change. Data on the real output of consumer and capital goods, on real capital input, and on productivity at

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both the aggregate and industry level require accurate price deflators that are adjusted for changes in quality.[1] Just as a price increase due solely to larger size or improved performance should not be allowed to raise the aggregate price index, but rather should be subject to a quality adjustment, so a price increase due solely to an engineering change that improves fuel economy should be subject to a similar quality adjustment rather than being treated as an increase in the aggregate price level.

Quality adjustments for changes in energy efficiency and other changes in user cost raise an important conceptual issue already familiar from the debate on quality changes in dimensional or performance characteristics of goods: should the criterion for quality adjustment be *production cost* or *user value*? Under the production (or resource) cost criterion, goods are considered of equal quality if they cost the same to produce. A difference in price between two models of a product would be adjusted for any difference in quality by subtracting from the price of the more costly model the amount by which its production cost exceeds that of the cheaper model. Under the user-value criterion, goods are considered of equal quality if they provide the same value to the user. A difference in price between two models would be subject to a quality adjustment based on the relative value of the two models to users, without regard to differences in the production cost of the two models.

In many cases the production-cost and user-value criteria lead to the same result. A competitive market leads to the production of "quality," for example, dimensional or performance characteristics, up to the point at which the real marginal cost of producing each characteristic is equal to the present value of its marginal product. A quality change resulting from a shift in the marginal value product of a characteristic, due to a change in product price or in the quantity of other inputs, takes place up to the point where the higher marginal value product is balanced by a higher production cost. In such cases quality adjustments based on the production-cost and user-value criteria are identical, and either method yields the same price deflator.

No new problems are posed for price measurement when there are changes in energy efficiency or other elements of user cost that take the form of proportional changes in production cost and in the present value of marginal product *net of operating costs.* A change in electricity prices, for example, tends to induce firms to produce more energy-efficient refrigerators, up to the point where the added production cost of insulation and other energy-saving devices is balanced by the present value of energy savings to users. The adjustment of a price difference between old model A and a more efficient model B can be handled by comparing production cost, and this difference in cost represents the difference in user value as well.

In such cases the normal "specification pricing" procedure of the U.S. Bureau of Labor Statistics (BLS) can handle changes in operating efficiency easily and routinely. If refrigerator model *A* is replaced by model *B*, which consumes less electricity but is otherwise identical, and if the manufacturer states that the entire price difference between the two models is due to the higher production cost of the better efficiency characteristics of model *B*, then the BLS would correctly record an absence of price change. What, then, justifies an entire paper devoted to the subject of the treatment of user-cost changes in price measurement?

4.1.2 Nonproportional Changes in Cost and Value

Numerous examples of quality change occur in which production cost does not change in proportion to user value, thus creating a difference between measures of quality change based on the production-cost and user-value criteria. In the past such quality changes have been misleadingly labeled "costless" but in fact are better termed "nonproportional." As seen below, the best way to characterize a nonproportional quality change is as a downward shift in the supply curve of user-desired characteristics. Examples of such shifts include the increased calculation ability of electronic computers of given size and resource content, the superior performance of the jet aircraft engine compared to the propeller engine it replaced, improvements in the picture quality of color TV sets without increases in cost, and improved fuel economy of automobile engines of given size and performance characteristics. These examples of nonproportional quality changes suggest that improvements in performance characteristics rarely occur without simultaneously involving changes in operating cost. The computer, jet aircraft, home appliance, and automobile industries all achieved savings in energy and maintenance requirements at the same time that performance innovations occurred.

The central issue in the quality change debate is the proper treatment of nonproportional changes in the construction of official price deflators. The "production-cost criterion" was originally set out by Edward Denison: "If the cost of two types of capital goods were the same (or would have been the same were both newly produced) in the year in whose prices the measures are expressed, they are considered to embody the same amount of capital regardless of differences in their ability to contribute to production" (1957, p. 222). The U.S. Department of Commerce has adopted the Denison production-cost criterion for purposes of deflating output.[2] Thus, if there is an innovation in the computer industry that doubles the calculation capacity of a computer without changing its production cost, the Denison criterion would treat both computers as the same quantity of investment and capital.

The contrasting position has been that user value should be the criterion for quality adjustment in those situations where quality change occurs but production cost and user value do not change in proportion.[3] Proponents of the user-value criterion often point to the computer industry as an important example in which use of the production-cost criterion leads to an understatement of increases in quality, in real investment, and in real GNP, together with an overstatement of increases in the aggregate price level.[4]

The distinction between the two criteria, however, is misleading. If the unit of measurement in the computer example were changed from "one computer" to "one calculation," then the production-cost criterion would correctly capture the reduction in cost per calculation and would lead to the same answer as the user value criterion. Recently, Triplett (see Chap. 5 this volume), building on the earlier work of Fisher and Shell (1972), has set forth a new analysis of quality change in which the units of measurement are a good's characteristics, for example, "calculations." He concludes that the production-cost criterion is correct for the construction of an output price index, while the user-value criterion is correct for the construction of an input price index. The effect of his analysis for the computer example is to yield a price index that accurately captures the reduction in the price of a calculation achieved by technical innovation and which thus satisfies those who have previously criticized the production-cost criterion for missing such reductions in price. The exposition in this paper, based on Triplett's analysis, shows that in many practical applications there is no longer any need to distinguish between the production-cost and user-value criteria of quality measurement.[5]

4.1.3 Plan of the Paper

A preliminary conceptual section sets the subsequent theory in the context of recent debates in the area of quality measurement. Among the topics treated are the meaning of the production-cost and user-value criteria, the distinction between input and output indexes that is central to the work of Fisher and Shell (1972) and Triplett (this volume), the conditions necessary for the prices of individual goods to be adjusted for changes in user cost, and the implications of the approach for productivity at the aggregate and industry level.

The theoretical analysis of operating cost changes involves a simple model in which producers' durable equipment varies along two dimensions, a composite performance characteristic, and a composite operating cost characteristic. Firms design each vintage of equipment to have a level of operating efficiency that is optimal, given the expected prices of operating inputs. Changes in specifications can respond to both changes in technology and changes in the expected prices of energy and other inputs and can lead to proportional or nonproportional changes in cost and user value. The model is used to analyze problems of extracting information on "true" price changes from observed changes in the price of a unit of equipment when changes in performance and operating efficiency characteristics occur.

The model can be applied not only to the measurement of price changes for new models but also to the analysis of changes in the prices of used models. Changes in operating characteristics, and in the prices of operating inputs, can alter both the prices and the service lifetimes of used assets. As a result the relative price of used and new assets may change, an effect that must be taken into account in any attempt that uses price data on used assets as a proxy for the unobservable transactions prices of new goods.

The ideas in the theoretical section are applied to the detailed practical problems involved in measuring the prices of an important type of producers' durable equipment—commercial aircraft. An application of the theoretical index formula yields a new deflator for the commercial aircraft industry that is radically different from the present official deflator. Although the new index mirrors the 6.2% annual rate of increase in the official index between 1971 and 1978, during the period 1957–71 its annual rate of increase is *minus* 7.5% annually, as opposed to the official increase of *plus* 2.6% per year. Among the implications of the new index is that as now measured productivity growth in the aircraft industry has been understated, and total factor productivity growth in the airline industry has been overstated.

4.2 Central Conceptual Issues

4.2.1 Input and Output Price Index Concepts

Triplett (this volume) has made Fisher and Shell's (1972) distinction between input and output price indexes the centerpiece of his analysis of quality change. Measures of real capital used as a productive input should be calculated using an input price index, according to Triplett, and measures of the output of the capital-goods producing industry should be calculated using an output price index. The following exposition, based on Triplett's analysis and concepts, examines the input and output price concepts in the case of technical innovations like those in the computer industry.

We begin by assuming that output (y) is produced by a vector of input characteristics (x). Since the primary focus of this paper is on the measurement of capital input and of the output of capital goods, henceforth we ignore labor input. One may think of y as ton-miles per truck per year and of x as including horsepower and truck size, or of y as the calculation services provided by a computer and x as including its memory size and ability to perform multiplications per unit of time. The flow of output that can be produced by a single unit of the durable good containing the vector of performance characteristics x can be expressed in a conventional production function:

(1) $$y = y(x), \qquad y_x > 0, y_{xx} < 0,$$

where y_x represents the partial derivative of y with respect to x.

The producers' durable good is manufactured under competitive supply conditions, according to a cost function that exhibits constant returns in the quantity of goods produced, and diminishing returns in the number of embodied units of the performance characteristic:[6]

(2) $$V(x) = Cc(x), \qquad c_x > 0, c_{xx} > 0.$$

Adopting the convention that lower-case letters represent "real" variables and upper-case letters "nominal" variables, we use c to represent the real unit cost function, C to represent shifts in the cost of producing a given product due to changing profit margins and/or input prices, and V to stand for the total value of each unit produced.

For any given level of technology, say that obtaining at time t, more inputs are required to produce more output. The input demand function depends on output and on the prices of inputs:

(3) $$x_t = x(y_t, C_t).$$

When the input demand function from (3) is substituted into the cost function of the supplying industry (2), it is seen that there is an indirect dependence of the cost of the good on the output produced by its user:

(4) $$V(x_t) = V(y_t, C_t) = C_t c[x(y_t, C_t)].$$

The criterion of comparison upon which the input price index (P_t^x) is based is that prices are compared holding constant output at a given level, say y^*. The optimal set of input characteristics (x^*) is defined by the demand functions for the characteristics at the given output level (y^*) and the differing input prices:

(5) $$x_t^* = x(y^*, C_t) \qquad \text{and} \qquad x_0^* = x(y^*, C_0).$$

The input price index can now be compared as the ratio of the cost (V) of obtaining the optimum (minimum-cost) combinations of the vector of input characteristics sufficient to produce output level y^* in the reference and comparison-period input price regimes. Thus the input price index is simply the ratio of (4) for the two price regimes, evaluated at the constant output level y^*:

(6) $$P_t^x = \frac{V(x_t^*)}{V(x_0^*)} = \frac{C_t c[x(y^*, C_t)]}{C_0 c[x(y^*, C_0)]}.$$

Because a change in input prices (C) between regimes can cause substitution in the quantities of the various input characteristics, the input price index allows for such substitution.

In this discussion the inputs into the production function are the individual characteristics of goods, the vector x, so that a quality change involves a change in the quantity of one or more productive characteristics, which in turn must change the level of output. Since any such quality change would thus violate the criterion of constant output (y^*) on which the input price index is based, price measures must be adjusted "for changes in input characteristics that result in changed output (or reduced cost to the user), and the correct quality adjustment is exactly equal to the cost change or the value of the output change that they induce. In the literature, this is known as the user-value rule" (Triplett, this volume, p. 286).

In contrast to the input price index, the output price index uses a standard that compares prices by holding constant the economy's endowment of productive factors and its production technology. Now we write the output symbol (y) as representing a vector of output characteristics. Triplett defines the output price index P_t^y as the ratio of the revenue (R) obtained from the optimum (maximum-revenue) combination of output characteristics in the reference and comparison-period output price regimes, holding constant both input quantities (x^*) and production functions $[y^* = y(x^*)]$:

$$(7) \qquad P_t^y = \frac{R(y_t^*, P_t)}{R(y_0^*, P_0)}\ .$$

Note that the numerator and denominator of the output price ratio differ both in the price regime and in the quantities of output characteristics (y_t^*) that are optimal, given the fixed input quantities (x^*) and the fixed production functions that establish the various output combinations that can be produced from those inputs.

A quality change now implies an increase in one or more output characteristics.[7] If we assume that the resources devoted to increasing quality are obtained by decreasing the output of some other good, in order to remain on the same production possibility frontier the output price index must be adjusted for the resource cost of the added output characteristics. "The [quality] adjustment required is equal to the value of the resources required to move the set of output characteristics included in the index back to the same production possibility curve. This is precisely the resource cost quality measurement rule that has been argued in the literature" (Triplett, this volume, p. 299).

4.2.2 Measuring the Input Price Index When Quality Change is Nonproportional

Nonproportional technical innovations raise the performance of a good by increasing its built-in quantity of characteristics (x) relative to the resources used by the supplying industry. Thus such innovations take the form of a downward shift in the real cost of producing a given quantity of characteristics, say computer calculations.

The idea of nonproportional quality change can be brought into the measurement of the input price index by introducing a shift term λ_t into the cost function (4):

$$V(y_t,C_t,\lambda_t) = C_t c[x(y_t,C_t),\lambda_t]. \tag{8}$$

It is important to note that there is no shift in the using firm's production function (1), since a single calculation still produces the same amount of output in the using industry. Thus the units of characteristics to be defined as x must be those which directly enter the using firm's production function, for example, a computer's "calculations per second" and not its dimensions.

In this framework the total change in input cost consists of four terms:

$$dV = dC(c + C_t c_x x_C) + C_t(c_x x_y dy + c_\lambda d\lambda). \tag{9}$$

These terms represent, respectively, the direct and indirect substitution effect of changing prices of the inputs to the supplying industry, the effect of changing input requirements due to changing output ($x_y dy$), and the effect of technical change in shifting the real cost function ($c_\lambda d\lambda$). Since the input price index (P_t^x) is the ratio of (8) evaluated for the comparison period to (8) evaluated for the reference period—holding the output level constant at y^*—the *change* in P_t^x can be written as the total change in cost minus the contribution to cost of the change in output:

$$\frac{dP^x}{P^x} = \frac{dV - C_t c_x x_y dy}{V(y^*,C_0,\lambda_0)} = \frac{dC(c + C_t c_x x_C) + C_t c_\lambda d\lambda}{V(y^*,C_0,\lambda_0)}. \tag{10}$$

Here the middle expression indicates that the change in price would be measured by adjusting the observed change in cost of a new model for the change in its quantity of characteristics ($x_y dy$) multiplied by the marginal cost of producing characteristics ($C_t c_x$). The right-hand expression shows that the price change can be caused either by changes in input prices or profit margins in the supplying industry (dC) or by a technical shift ($d\lambda$). Because the middle expression is used in actual measurement, the technical shift itself ($d\lambda$) does not have to be observed directly.

Figure 4.1 illustrates the measurement of changes in the input price index in the presence of nonproportional quality change. The two upward sloping lines plot the unit cost function (eq.[8]) for two different values of the technical shift parameter λ. Initially, output level y^* is produced at an input unit cost of V_0 at point A. The technological shift represented by the higher value of λ improves quality by raising the quantity of input characteristics relative to their cost. This raises the demand for characteristics and the level of output, depicted by y_1 in the diagram. The unit cost

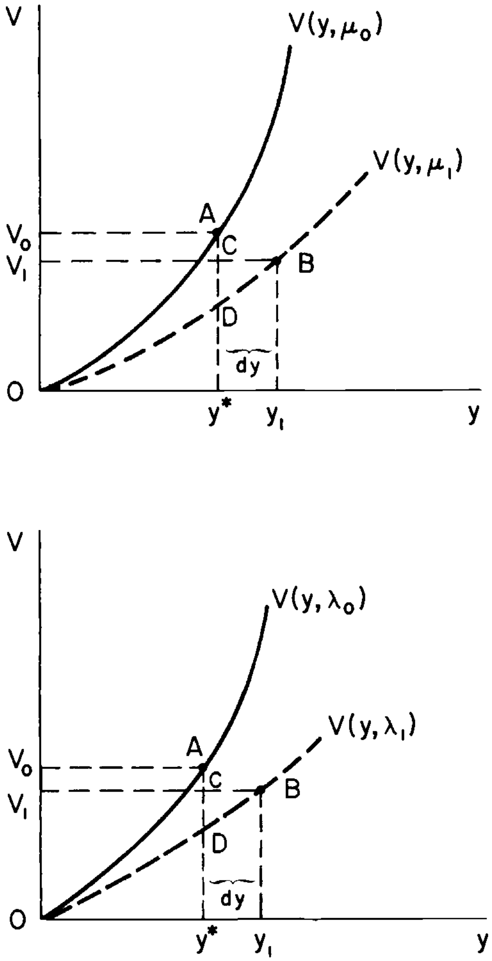

Fig. 4.1 Effects on input cost and output of a technological shift that raises the quantity of input characteristics relative to their cost.

of the durable good (V_1) could be either higher or lower than in the initial equation (V_0).

According to equation (10), the change in the input price index is equal to the change in unit cost (minus line segment AC) minus an adjustment factor equal to the change in output (CB) times the marginal cost (CD/CB) of building extra input characteristics capable of producing the extra output along a new supply schedule. Thus the change in the input price index is $-AC - CD = -AD$, that is, the vertical downward shift in the supply schedule itself. Note that the change in the real input quantity is measured by the change in output times the marginal cost of producing extra output under the new supply conditions. The change in an index of the real quantity of input characteristics (dQ^x) can be written formally as the proportional change in the number of units of capital (du/u), plus the change in cost per unit (dV/V), minus the input price index:

$$\frac{dQ^x}{Q^x} = \frac{du}{u} + \frac{dV}{V} - \frac{dP^x}{P^x} = \frac{du}{u} + \frac{C_t c_x x_y dy}{V(y^*, C_0, \lambda_0)} . \tag{11}$$

Because it is the marginal cost of producing characteristics that is used to make the actual quality adjustment in (10), the distinction between the "user-value" and "production-cost" criteria for the measurement of quality change is misleading, since both are used in (10) and in the corresponding figure 4.1. User value is the criterion used to define x, that is, the choice of calculations rather than dimensions as the characteristic desired by the user. And production cost is the criterion used to make the actual quality adjustment. The earlier literature (as exemplified by the Denison quote in Section 4.1.2, e.g.) did involve a meaningful distinction between the two criteria, because the production-cost criterion was being applied to units of goods (u) rather than user-desired characteristics (x). Now, however, with the quality measurement procedure stated in terms of characteristics, we have a hybrid criterion in which both the user-value and production-cost criteria are integral parts.

For the purpose of quality adjustment in practice several alternative methods of estimating the marginal cost (c_x) are available. For instance, if an auto manufacturer were to make automatic transmission standard at no increase in price, and the BLS had information either on the price of automatic transmission when it was an option, or a manufacturer's estimate of the cost of producing an automatic transmission, then the present BLS pricing methodology would be adequate to measure the marginal cost. Often, when quality change involves continuous rather than discrete change, for example, a change in automobile acceleration and dimensions, or in computer performance, it is more convenient to use the hedonic regression technique to estimate the shadow price of a given characteristic, that is, its marginal cost. Clearly the proper technique to use in each case is independent of whether the nature of the quality change is "cost increasing" or "nonproportional."

4.2.2 Measuring the Output Price Index When Quality Change is Nonproportional

We now turn to the output price index and ask whether it gives a consistent treatment to an identical technological innovation. We imagine that the input price reduction depicted in figure 4.1 occurs because of a cost-saving technological innovation in the electronic computer industry. In this case, what happens to the output and price indexes for the value added of the computer industry, a component of real GNP? The nonproportional quality change can be introduced into the discussion of output price indexes by allowing the same shift term (λ) to enter the production function of the computer industry. A vector of output characteristics (y) is now produced in an amount that depends on the quantity of input characteristics (x), the relative prices of output characteristics (P), and the shift term (λ):

$$(12) \qquad y = y(x,P,\lambda), \qquad y_x > 0,\ y_\lambda > 0.$$

The output price index is now the ratio of revenue in two periods when output prices are allowed to change, holding constant the level of resources (inputs) and production technology:

$$(13) \qquad P_t^y = \frac{R(y_t^*,P_t)}{R(y_0^*,P_0)} = \frac{P_t y(x^*,P_t,\lambda^*)}{P_0 y(x^*,P_0,\lambda^*)}\,.$$

The total change in revenue between the reference and comparison periods is the total derivative of the revenue function:

$$(14) \qquad \frac{dR}{R} = \frac{dP(y + P_t y_P) + P_t(y_x dx + y_\lambda d\lambda)}{P_0 y(x^*,P_0,\lambda^*)}\,,$$

where the terms represent, respectively, the direct and indirect substitution effects of changes in the output price, the effect on real output of increasing input usage, and the effect on real output of the technological shift itself.

The change in the output price index (13) consists of only two of the four terms in (14), since both input usage (x^*) and technology (λ^*) are being held constant:

$$(15) \qquad \frac{dP^y}{P^y} = \frac{dR - P_t(y_x dx + y_\lambda d\lambda)}{P_0 y(x^*,P_0,\lambda^*)} = \frac{dP(y + P_t y_P)}{P_0 y(x^*,P_0,\lambda^*)}\,.$$

The corresponding quantity index based on the output price index consists of the residual change in revenue:

$$(16) \qquad \frac{dQ^y}{Q^y} = \frac{P_t(y_x dx + y_\lambda d\lambda)}{P_0 y(x^*,P_0,\lambda^*)}\,.$$

What is the relationship between changes in the output price index and input price index defined by (10)? Figure 4.2 illustrates the calculation of changes in the output price index and quantity index when there is a technological change represented by a shift from λ_0 to λ_1. The increase in the output that can be produced by the initial resource endowment raises output directly by the term $y_\lambda d\lambda$ in equation (15), and indirectly by raising the marginal product of inputs and hence the demand for inputs (the term $y_x dx$). If the higher level of output is to be sold, the output price (P) must

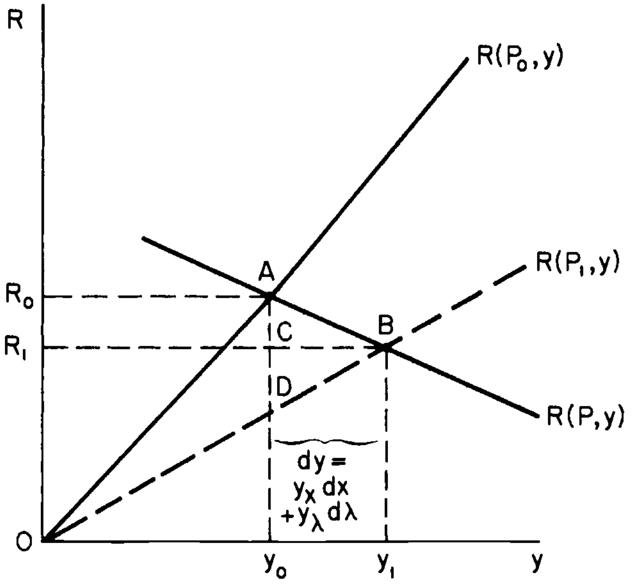

Fig. 4.2 Effects on revenue and output of a technological shift that raises the level of output relative to the quantity of input characteristics.

drop, as indicated along the appropriate industry demand curve. The downward sloping total revenue line in figure 4.2 is drawn on the assumption that demand is price inelastic. The upward sloping lines indicate the revenue that would be obtained from varying levels of output if the price level were fixed. Starting from an initial equilibrium at point A, the innovation-induced increase in output leads to a new equilibrium at point B, where the price level has dropped from P_0 to P_1, and total revenue has declined from R_0 to R_1. According to equation (15), the change in the output price index is measured by the change in revenue (minus the line segment AC) minus the new price level (CD/CB) times the change in output (CB), or the distance $-AD$.

Now the connection between figures 4.1 and 4.2 becomes evident. When we consider the output of a capital good, for example, an electronic computer, a technological shift causes a decrease in price measured by the vertical distance AD in figure 4.2. We note that this vertical downward shift AD also appears in figure 4.1 as the change in input prices as viewed by the user of the electronic computer. Once again, the input and output price index concepts are equivalent and would include in both real GNP and in real capital input technological shifts that raise the output capacity of capital goods relative to their production cost.

The model is equally applicable to "resource-using" or "cost-increasing" quality change. Imagine an upward shift in the demand for computers, without any change in technology. The previous equations are appropriate for measuring price and output change if we set the $d\lambda$ terms equal to zero. In figure 4.1, imagine an initial equilibrium at point D, where the lower supply curve meets an initial demand curve (not drawn). Then let the demand curve shift upward sufficiently to move the new equilibrium position to point B. The change in unit cost (dV) is exactly offset by the increase in the marginal cost of the additional characteristics, leaving the input price index as measuring shifts in the price of producing a given output; in this case there has been no such shift. The same conclusion applies to the output price index, which would be measured as unchanged, since the price of utilizing the initial level of resources has remained unchanged.

The major conclusion of this section has been that in principle both input price indexes and output price indexes treat quality change consistently, and the user-value and production-cost criteria lead to the same measures of prices and real output. This has always been recognized as true for "resource-using" quality change, where an increase in quality requires an increase in production cost. The novelty in this section is the demonstration that "nonproportional" quality change is also treated consistently by properly defined input and output indexes. Thus a technological change that raises the user value of a durable good relative to its production cost will be measured *in exactly the same way* in indexes of the real output of the industry producing the durable good and of the real capital input of the industry using the durable good.

4.3 A Model Incorporating Operating Costs

4.3.1 Energy Embodiment and Separability

Some recent research on the production technology of energy use, for example, Hudson and Jorgenson (1974), assumes that energy (e) enters the production function symmetrically with labor hours (h) and capital input (x):

$$y = y(h,x,e), \qquad y_h>0, y_x>0, y_e>0. \tag{17}$$

Thus changing relative prices, in particular the rising relative price of energy observed during the 1970s, can cause substitution both between energy and capital, and energy and labor. Because the price of labor influences the amount of labor used per unit of capital, there is no presumption in this framework that changes in energy efficiency call for adjustments in the prices of capital goods. Indeed, in his Comment on this paper Triplett prefers that changes in energy efficiency be reflected in measures of the user cost of capital (including interest, depreciation, energy, and labor usage), but not in price indexes needed to create estimates of the output and productivity of industries that produce capital goods.

Yet Triplett's position appears to prevent the consistent treatment of performance-increasing and energy-saving technological change in the measurement of prices, output, and productivity. The previous section shows why a technological shift in the performance of a capital good per unit of resources used in capital-goods-producing "Firm A" should be treated as an increase in real investment and real GNP. Now let us assume that another capital-goods-producing "Firm B" achieves a technological improvement in one of its products, yielding energy savings to users of equal value to the performance improvement achieved by Firm A. Should not the criteria for price measurement be designed to treat both types of technological change symmetrically?

In order to adjust the price of a capital good for changes in energy efficiency, it is necessary to assume that energy usage is "embodied" in capital goods and that the production function (17) can be rewritten in the separable form:

$$y = y[h,k(x,e)], \tag{18}$$

where $k(x,e)$ is a subfunction with two inputs, performance characteristics (x) and energy (e), which produces capital input (k). Berndt and Wood (1979) describe the subfunction as follows:

> For example, consider the production of industrial process steam of given specified physical characteristics. In such a context utilized capital services (k) refers to the quantity of steam produced per unit of time using capital . . . and fuel inputs. This assumption of a separable utilized capital subfunction implies that the optimal e/x ratios . . . depend solely on (the prices of x and e and not on the other input prices) or the level of gross output y.[8]

Is this assumption of separability, which is essential to the discussion of price measurement in this paper, a reasonable one or, as Triplett claims, arbitrary and "unrealistic"? Three arguments can be presented to support the procedures proposed here:

1. Berndt and Wood (1979) have reexamined previous econometric studies in an attempt to reconcile disparate findings regarding the degree of substitution or complementarity between capital and energy. In these reconciliations "separability has played a prominent role" (p. 350), and their own empirical (1975) appears to support the separability assumption.

2. The study below makes the assumption not only that the production function is separable but that technology is "putty-clay," so that energy

usage is "designed in" when the capital good is built. In some industries the assumption that energy requirements are embodied in capital goods seems more reasonable than in others. The ability of a user to improve the energy consumption of an automobile, commercial airplane, electricity generating plant, or appliance is relatively minor compared to the latitude available to the manufacturer. Thus, a Cadillac owner might improve his gas mileage from 14 to 15 miles per gallon by careful driving habits, but to achieve 40 miles per gallon he would have to buy a Chevette or Honda.

3. Although users can alter energy consumption even when technology is putty-clay, for example, an automobile driver can save gasoline by careful avoidance of sudden starts, the techniques described below involve measuring an energy requirements function that holds constant the characteristics of users. In addition, performance characteristics are held constant, yielding a function translating energy into performance that fairly can be said to be under the control of the capital-goods manufacturer.

4.3.2 Adapting the Input Price Index to Incorporate Nonproportional Changes in Net Revenue

We now assume that the production of output (y) requires not only the acquisition of durable goods having productive input characteristics (x) but also involves a variable operating cost, the consumption of other inputs (e) times their price (S). In the present discussion e may be taken to represent the yearly consumption of energy of a capital good having performance characteristics x. The energy requirements function is taken as given by the equipment user, reflecting our assumption of a separable putty-clay technology:

$$e = e(x,\sigma), \qquad e_x > 0, e_\sigma < 0, \tag{19}$$

where the parameter σ represents a technological shift factor that can alter the energy consumption of a given set of input characteristics.

The net revenue (N) of the durable good user consists of gross revenue less variable operating cost. Gross revenue is the output price times the production function (eq. [1] above) that allows for technical change, and operating cost is the price of the operating input (S) times the consumption of operating inputs (e):

$$N = Py(x) - Se(x,\sigma). \tag{20}$$

An expression for real net revenue (n) can be obtained by dividing (20) by the output price:

$$n = y(x) - se(x,\sigma), \tag{21}$$

where s is the real price of the operating input ($s = S/P$).

Recall that the input price index was previously defined as the ratio for two time periods of the nominal cost of inputs that are capable of producing a given level of output (y^*). A natural extension of this concept in the presence of variable operating costs is to hold constant between the two periods the level of real net revenue (n^*). This criterion reflects the assumption that users of durable goods do not care about the gross output produced but rather about the net revenue that the durable goods provide. Thus a user is assumed to be indifferent between 10 units of real net revenue obtained from a situation with 15 units of output and five units of real operating cost, and an alternative situation with 16 units of output and six units of real operating cost, holding constant his investment in capital goods.

The introduction of variable operating costs makes the demand for input characteristics depend on real net revenue (n), the vector of prices of input characteristics (C), the real price of operating inputs (s), and the technological shift parameter (σ):[9]

$$x_t = x(n_t, C_t, s_t, \sigma_t), \qquad x_n > 0, x_s > 0, x_\sigma < 0. \tag{22}$$

Comparing the arguments here to the previous input demand function in equation (3) above, we note that real output has been replaced by real net revenue and that the two parameters of variable operating cost have been added (s and σ). The signs of the derivatives of (22) assume that the firm is operating in the region in which additional net revenue requires extra input to produce more gross output.[10] An increase in operating cost requires an increase in gross output (and hence capital input) to yield any fixed level of net revenue; hence the derivative is positive with respect to the relative price s and negative with respect to the technological parameter σ.

When the new input demand function in (22) is substituted into our input characteristic cost function that allows for technical change (equation 8 above), we obtain an expanded equation for the cost function:

$$V(n_t, C_t, s_t, \sigma_t, \lambda_t) = C_t c[x(n_t, C_t, s_t, \sigma_t)\lambda_t]. \tag{23}$$

Now the input price index is defined as the ratio of the cost function in the comparison period to that in the reference period of producing the same real net revenue, holding constant the relative price of operating inputs:

$$P_t^x = \frac{V(n^*, C_t, s_0, \sigma_t, \lambda_t)}{V(n^*, C_0, s_0, \sigma_0, \lambda_0)}. \tag{24}$$

The decision to hold constant the relative price of operating inputs (s) in the numerator and denominator reflects the desire to limit changes in the input price index to factors internal to the firm manufacturing the durable good—its input prices and profit margin (C) and the level of technology built into the good (σ, λ). In this way changes in the relative price of an operating input like energy are not treated as changes in the price of capital input.

Now the change in the input price index can be written in two equivalent ways:

$$(25)\qquad \frac{dP^x}{P^x} = \frac{dV - C_t c_x(x_n dn + x_s ds)}{V(n^*, C_0, s_0, \sigma_0, \lambda_0)} = \frac{dC(c + C_t c_x x_C) + C_t(c_x x_\sigma d\sigma + c_\lambda d\lambda)}{V(n^*, C_0, s_0, \sigma_0, \lambda_0)}.$$

The extended model incorporating operating costs can be illustrated in figure 4.3, which repeats the axes of figure 4.1. The upward sloping schedule plots equation (23) and shows the increasing unit cost of input characteristics required to generate additional net revenue. The initial equilibrium position, where the quantity of output is chosen to make marginal net revenue equal to marginal cost, is shown at point *A*.

We consider first the proper treatment in price measurement of an improvement in quality that occurs when an equiproportionate increase in the prices *P* and *S* relative to *C* leads users to demand higher quality capital goods. Because the higher prices *P* and *S* shift the nominal

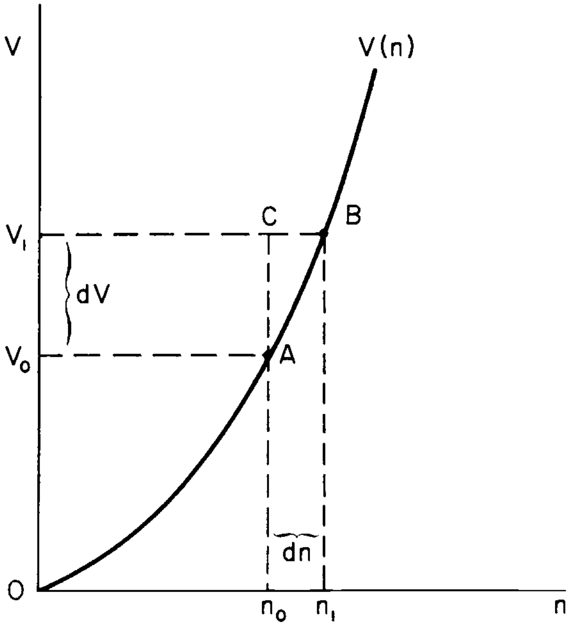

Fig. 4.3 Effects on input cost and net revenue of an equiproportionate shift in the nominal prices of output and energy.

marginal net revenue schedule upward, the equilibrium position shifts from A to B. If the manufacturer reports to the BLS that the entire addition to the price of the good from V_0 to V_1 is due to the higher cost (CA) of raising the specification of characteristics embodied in the good, the BLS would correctly conclude that there has been no price change. We note that the manufacturer's cost estimate does not represent simply the effect of higher x holding constant operating cost but rather the net extra cost of raising x while allowing energy consumption to increase along the $e(x)$ function. There is no danger that the substitution toward greater operating cost will be misinterpreted as a change in input price as long as the marginal cost (CA/CB) of the extra quantity of input characteristics is correctly measured.

Does the general formula (25) for the change in the input price index correctly conclude that there has been no price change? From the change in the cost of the durable good (CA) is to be subtracted the marginal cost (CA/CB) of the extra input characteristics required to raise real net revenue by the actual observed amount (CB). Thus the observed change in input cost (CA) minus the correction factor (CA) equals zero.

A second case, a reduction in the relative price of energy, is illustrated in figure 4.4. A decrease in the price of energy from S_0 to S_1, while the product price is held constant at P_0, shifts the unit cost schedule rightward, since a smaller nominal operating cost must be deducted from gross revenue for any given quantity of the input characteristic x, thus raising net revenue for any given value of V. The new equilibrium position is assumed to shift from point A to B. The input price index subtracts from the observed change in price (CA) the marginal cost (CD/CB) of the extra input characteristics required to raise real net revenue by the observed amount (CB) adjusted for the effect on input cost ($+AD$) of lower energy prices (ds) when real net revenue is constant. Once again, the observed change in input cost (CA) minus the correction factor ($-CD+AD$) equals zero.

As an example of this second case, we note that lower relative gasoline prices in the 1950s and 1960s induced firms and consumers to shift to larger automobiles that consumed more fuel.[11] But if an automobile with *given* horsepower had maintained its previous fuel consumption along a fixed $e(x)$ schedule, then no change would be imputed to the price of automobiles as a result of this substitution toward greater fuel consumption. (Wilcox [1978] has found, however, that during this period the fuel requirements function was not fixed.)

As a third example, let us consider a technological innovation that allows a given quantity of the input characteristic (x) to be used with a smaller consumption of fuel. To simplify the illustration in figure 4.4, it will be assumed that the shift takes the special form of reducing the marginal energy cost of a change in input quantity by the same amount as

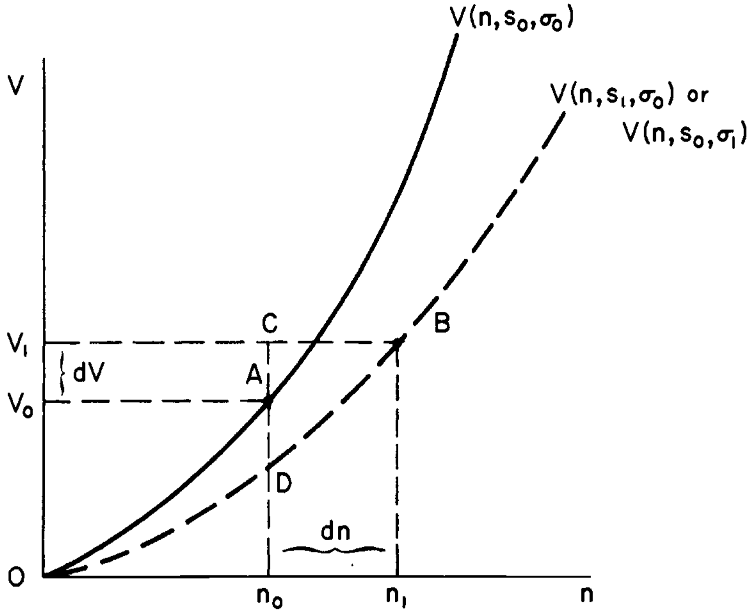

Fig. 4.4 Effects on input cost and net revenue of (*a*) a reduction in the relative price of energy, and (*b*) an innovation that improves fuel efficiency.

the decrease in the relative energy price examined in the previous two paragraphs:

(26) $$s_0 e(x,\sigma_1) = s_1 e(x,\sigma_0).$$

Now the lower schedule in figure 4.4 is relabeled to correspond to the new, more efficient consumption schedule in which σ_1 replaces σ_0.

In this third case, as in the first two cases, the equilibrium position moves from point *A* to point *B*. But now the input price index registers a decline in price instead of no change in price. From the change in the unit cost of the input characteristic ($dV = CA$) is subtracted the marginal cost (CD/CB) of the extra input characteristics required to raise real net revenue by the actual observed amount (CB). Thus the observed change in input cost (CA) minus the correction factor (CD) equals the change in the input price index ($-AD$).

4.3.3 Implementation of Operating Cost Adjustments

In each of the cases considered in the previous section, the observed change in unit cost of a durable good was adjusted for changes in net revenue caused by a shift in either an exogenous price or technological parameter. In each case the adjustment involved determining the marginal cost of whatever extra quantity of input characteristics would have been required to yield the observed increase in net revenue in the absence of the observed parameter shift. How is this adjustment factor to be measured in practice?

The discussion of measurement can usefully be set in the context of a competitive firm that uses capital goods to produce net revenue. Its user cost of capital multiplies the unit price of a durable good (V) times the interest rate r (representing some combination of borrowing costs and the opportunity cost of the firm's own funds), plus a geometric depreciation rate δ that measures the rate of decay with the asset's age of the stream of services that it provides. The capital market is assumed to set only a single interest rate that each firm takes as given.[12]

Firms using the durable good are price takers in both input and output markets. They have no influence on the price of the durable assets they purchase (V), on the price of the output they produce (P), or on the price of operating inputs (S) or cost of ownership ($r+\delta$) they must pay. They simply choose the level of output that maximizes yearly profit (π), the difference between nominal net revenue (from eq. [20]), and the user cost of capital:

$$\pi = N - (r+\delta)V = Py(x) - Se(x,\sigma) - (r+\delta)V(x). \tag{27}$$

The only choice variable in the simplified structure of (27) is the quantity of input characteristics (x). If all producers and users of the durable asset are identical, then there will be a single model produced that embodies enough of the durable input characteristic to equate its real marginal cost of production to the present value of its real marginal net revenue:

$$v_x(x) = \frac{y_x(x) - se_x(x,\sigma)}{r+\delta} = \frac{n_x(x,s,\sigma)}{r+\delta}, \tag{28}$$

where $v_x(x) = V_x(x)/P$. The fact that the market usually provides numerous varieties containing different quantities of input characteristics has been explained by Rosen (1974) as resulting from the different tastes of consumers and technologies of producers.[13]

Figure 4.5 illustrates the equilibrium described in equation (28), with the real unit cost of durable goods on the vertical axis and real net revenue on the horizontal. As in figures 4.3 and 4.4, the purchase of additional input characteristics raises both unit cost (v) and net revenue (n), but the response of net revenue exhibits diminishing returns, both because of diminishing returns in the production function relating output to input characteristics, and also because of the increasing marginal cost of producing input characteristics. When the technical level of operating efficiency is represented by σ_0, the initial equilibrium occurs at point A, where the $v(n,\sigma)$ function is tangent to a straight line having the slope

$1/(r+\delta)$. The $v()$ function also depends on C/P and s, but these parameters are held constant in the present discussion of adjusting capital input prices for changes in operating efficiency, $d\sigma$.

If the level of operating efficiency were to shift to the improved level represented by σ_1, the firm would move to a new equilibrium position at point B, where the new $v(n,\sigma)$ function again has the slope $1/(r+\delta)$.[14] The change in the input price index, as in figure 4.4, is the observed change in unit cost (dv = line segment CA) minus an adjustment factor equal to the observed change in net revenue ($dn = CB$) times the marginal cost of producing input characteristics capable of providing that amount of net revenue, the slope CD/CB. Although points A and B can be observed, and thus dv and dn can be measured, point D cannot be observed directly. How can the slope CD/CB be calculated in practice in order to compute the quality change adjustment factor AD?

As figure 4.5 illustrates, the problem of estimating point D arises because of the curvature of the $v(n,\sigma)$ function. If the function were a straight line, then the unobservable point D would coincide with point D', which lies along a ray from the origin to point B having the slope

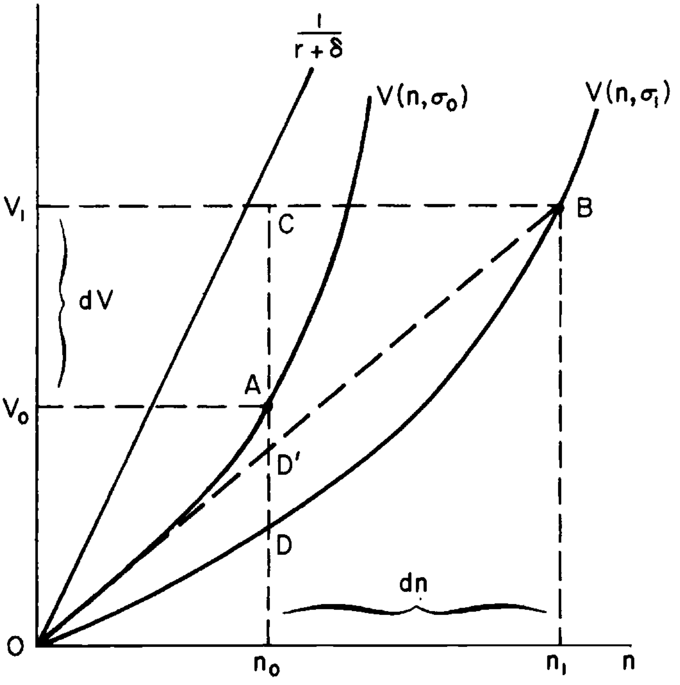

Fig. 4.5 The calculation of a quality adjustment when there is an innovation that improves fuel efficiency.

v_1/n_1. But, as long as there are *either* (a) diminishing returns in producing net revenue in response to an increase in the quantity of input characteristics or (b) an increasing marginal cost of producing input characteristics, then the curvature of the function will always make point D' lie above point D, and will make the segment AD' an underestimate of the required quality adjustment, segment AD.

Since the exact form of the function is unobservable, and because data are unlikely to be available to estimate it in many cases, the estimation of the quality adjustment factor must inevitably be based on some assumption about the function. Consider, for instance, the particularly simple relationship:

$$v = \beta n^{\alpha}, \tag{29}$$

where the curvature of the function depends on the parameter α. Technological changes that alter the position of the function are represented by shifts in the β parameter.

To use this function in the estimation of changes in input price, we first rewrite the basic formula (25) for a comparison in which the price of operating inputs (ds) is held constant:

$$\frac{dp^x}{p^x} = \frac{dv - v_n dn}{v_0}, \tag{30}$$

where the real unit cost (v) of the capital input replaces nominal cost (V) on the assumption that the output price can be held constant while comparing the new and old types of durable goods. Converting (30) from continuous to discrete changes, we obtain:

$$\begin{aligned} \frac{\Delta p^x}{p^x} &= \frac{\Delta v - [v(n_1,\sigma_1) - v(n_0,\sigma_1)]}{v(n_0,\sigma_0)} \\ &= \frac{v(n_0,\sigma_1)}{v(n_0,\sigma_0)} - 1. \end{aligned} \tag{31}$$

When the assumed functional form (29) is substituted into the general formula (34), the resulting expression depends only on observable variables and the "curvature" parameter:

$$\frac{\Delta p^x}{p^x} = \frac{\beta_1 n_0^{\alpha}}{\beta_0 n_0^{\alpha}} - 1 = \left(\frac{v_1 n_0}{v_0 n_1}\right)\left(\frac{n_0}{n_1}\right)^{\alpha - 1} - 1. \tag{32}$$

To make sense of the right-hand side of (32), imagine first that the $v(n,\sigma)$ function is linear, that is, that $\alpha = 1$, so that the second term in parentheses becomes unity. Then the remaining expression states that the "real" price change will be zero if both unit cost and net revenue grow in proportion in the shift to the new model, $(v_1/v_0) = (n_1/n_0)$. This is the case of "resource-using" or "cost-increasing" quality change. A nonproportional quality change, as illustrated in figure 4.5, would raise net revenue relative to cost and would result in an estimated change in the "real" input price index that is less than the observed change in price of models that remain identical.

When the $v(n,\sigma)$ function is nonlinear, then $\alpha > 1$, and the second term in parentheses in (32) becomes a fraction less than unity, corresponding in figure 4.5 to the fact that the unobservable point D lies below point D'. There seems to be no alternative in the estimation of equation (32) to making an arbitrary assumption about the value of the α parameter, or to presenting results for several alternative assumptions regarding the curvature of the $v(n,\sigma)$ function.

It is important to note that (32) is to be used to calculate a quality adjustment when comparing two different models, while holding constant output prices and the prices of operating inputs. Since this means in practice that the net revenue performance of two models must be compared in a particular year when both are in operation, equation (32) must implicitly be holding constant any factors that change the cost of manufacturing a given model in the given year of comparison, that is, changes in profit margins and/or the prices of inputs into the manufacturing process. Thus for practical measurement, equation (32), which computes the price change involved in the shift from one model to another, must be combined with an index of changes in the cost of producing identical models. Changes in the *nominal* input price index, then, are equal to changes in the *real* input price index plus changes in the cost of producing identical models:

$$\frac{\Delta P^x}{P^x} = \frac{\Delta p^x}{p^x} + \frac{\Delta C[C_t c_x(x^*)]}{C_0 c(x^*)} . \tag{33}$$

Thus, if there is a 10% annual increase in the price of identical models, and all quality change is resource using as in figure 4.3, the quality change adjustment in equation (32) will be zero, and the nominal input-cost index in (33) will be recorded to increase at a 10% annual rate. But if the real quality change adjustment were minus 5%, then the increase in the nominal input-cost index would be reduced to a 5% annual rate.

4.4 A Case Study of Innovations in the Commercial Aircraft Industry

4.4.1 General Procedures

Most empirical work in the quality change literature in the past two decades has involved the estimation of hedonic regression equations in which the price (unit cost) of durable goods is the dependent variable.

More recently the appearance of new econometric studies has become less frequent, while the list of critical interpretations and survey papers has been growing.[15] In none of this literature, however, is there any significant discussion of the treatment in price measurement of changes in operating efficiency.

This oversight is easily understood in the context of our present simplified model of the production and operation of durable goods. At any given level of technology (σ constant), operating cost and particularly energy consumption tends to be a function of the quantity of input characteristics (x) embodied in each durable good. Any given cross-section hedonic regression of price on the quantity of input characteristics can provide no useful information about the effect on price of changes in energy efficiency, if the fuel consumption and input quantities are collinear, and if shifts in the level of fuel efficiency take place on all models at the same time.

There is another and perhaps more fundamental reason why the traditional hedonic regression approach cannot identify the value of changes in fuel economy, even if shifts in the level of fuel efficiency do not take place simultaneously on all models. As we shall see in the aircraft examples below, the net revenue advantage of new, more fuel-efficient models has not been fully reflected in a higher price, but rather the small price differentials set by firms have transferred the benefits of the efficiency advantage to the airlines and ultimately to their customers in the form of lower prices and lower load factors. Thus the dependent price variable in the hedonic regression does not exhibit sufficient variation to allow the analyst to capture the full value to users of improvements in fuel economy.

The aircraft example in this section is provided to suggest practical methods of implementing the rather general and abstract measurement framework outlined earlier in the paper. The basic formula for quality adjustment, equation (32), requires the comparison of the observed change in the price of a new model with the extra net revenue that the new model provides relative to the old model, holding constant the prices of output and operating inputs. Because data on changes in net revenue are required, ideal testing grounds for the methodology are regulated industries in which the government requires the publication of detailed information on the operating costs of given pieces of capital equipment.

The case study of airlines presented below can be duplicated for other regulated industries, particularly for the generating plants used by electric utilities. Other types of capital goods, for example, automobiles, raise different problems of estimation, because no data are available on the output of automobile services to consumers, and thus the level of net revenue cannot be calculated. The conclusion to the aircraft case study suggests means of dealing with the problems of quality adjustment in other industries.

4.4.2 Index of Sale Prices of Identical Models

The commercial aircraft industry has all the qualifications to be a perfect case study of our methodology. The major customers of the U.S. commercial aircraft industry are the U.S. airlines, which have been subject to government regulation throughout the postwar period and have been required to make available to the public incredibly detailed information on traffic by route as well as operating costs by airplane type and station location. Further, the airline production function clearly meets the separability requirement discussed above; the predominant determinant of fuel consumption per airplane seat-mile is the basic design of the manufacturer, and the pilot has only minor latitude to alter fuel consumption by varying speed and shutting down engines while taxiing.

Finally, the dramatic nature of the transition from piston airplanes to jet aircraft makes the aircraft example an interesting one. This innovation simultaneously increased gross revenue by raising aircraft size and speed, while reducing operating costs per seat-mile. In fact, any estimate of the value to users of the transition to jet aircraft will inevitably be too conservative if it concentrates solely on the net revenue of the airlines and omits the value to users of the time savings made possible by increased speed and the comfort value of reduced vibration. Yet this paper eschews these subjective areas in the belief that a careful treatment of objective revenue and cost data is sufficient to establish the presence of previously unmeasured quality change.

The existing national income accounts deflator for the aircraft category of purchases of producers' durable equipment is compiled by the U.S. Civil Aeronautics Board (CAB), Bureau of Operating Rights.[16] Since airlines are required to report regularly the historic cost for each individual aircraft in their fleet, and since these aircraft are identified on CAB form 41 by their month of acquisition and exact type (e.g., Boeing 707-331-B), the CAB has been able to construct an aircraft price index by measuring the year-to-year change in the unit price for each type of equipment delivered in *both of two adjacent years.* Because only identical pieces of equipment are compared in adjacent years, the index ignores any "true" price change involved in the transition from one aircraft type to another. As an example, the substantial price reduction involved in the switch by Douglas in 1958–59 from the manufacture of the DC-7 to the DC-8 is completely ignored, and the price index for the years of transition is based only on price changes for planes that were manufactured in both of the adjacent years. Thus the CAB index corresponds to the dC/C term in equation (33). Because the CAB methodology ignores technical change, it is not surprising that from 1956 to 1977 the aircraft deflator rose 97%, little different from the 117% increase of the aggregate GNP deflator over the same period.

The methodology proposed above adjusts changes in prices of identical models by comparing changes in price per unit across model changes with changes in the net revenue provided. Unit prices of commercial aircraft are obtained from the same source as the official deflator, CAB form 41.[17] Because only a sample of prices has been collected for the period 1946–78, rather than all of the information available at the CAB, we first display as the lower solid line in figure 4.6 an index constructed from our sample of price data using the CAB methodology. Because different airlines paid different prices for the same aircraft, our index compares *only identical plane types purchased by the same airline in successive years.* For the years 1957–77 our solid-line index tracks the CAB index (dashed line) extremely well, with respective annual rates of increase of 3.41% and 3.55%. Before 1957 our index exhibits a slower rate of increase than

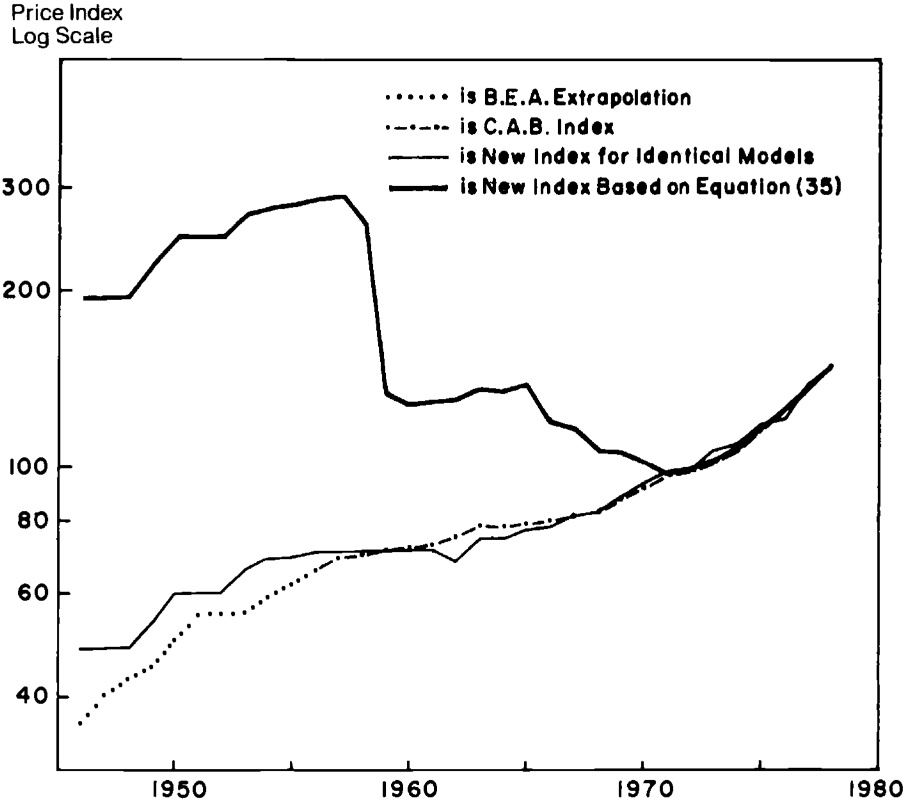

Fig. 4.6 The new quality-adjusted price index for commercial aircraft compared with a new index for identical models and with the BEA/CAB index.

the official deflator, which is extrapolated by the Bureau of Economic Analysis (BEA) for the earlier period when the CAB index is unavailable, by using a collection of producer price indexes that are unrelated to aircraft manufacture.[18] Thus our index indicates that during the interval 1946–57 aircraft prices increased less than the prices of the products used by the BEA in its proxy index, with annual rates of increase of 3.55% and 5.81%, respectively.

4.4.3 Quality Adjustments Based on Net Revenue Data

The technique of price measurement proposed in this paper adjusts price differences between models of a given product for changes in net revenue yielded by new models. Holding constant the prices of unchanged models, if a 10% increase in the price of model *B* compared to model *A* is accompanied by a 10% increase in net revenue, no quality adjustment is required to an index of the prices of identical models. But a disproportionate increase in net revenue made possible by embodied improvements in technology is valued by users and should be subject to a quality adjustment.

Table 4.1 presents the basic data required to compute the net revenue yielded by the most important types of commercial aircraft manufactured during the postwar period. Twelve comparisons appear in the table, involving 15 different aircraft models, including long-range, medium-range, and short-range models. In size the aircraft range from the small, two-engine piston short-range Convair 440, with 44 seats, to the large wide-bodied long-range turbofan Boeing 747, with 317 seats and capable of providing 28 times the annual capacity. In chronological time the aircraft models span the entire period 1946–78, beginning with the staple of early postwar air travel, the Douglas DC-6, and continuing through the planes that have carried the vast majority of U.S. air travelers in the late 1970s—the Boeing 747, Douglas DC-10, Boeing 727-200 and 727-100, and the Douglas DC-9-30. The major types of aircraft that are excluded (to limit the time devoted to the analysis) include planes that are virtual duplicates of those analyzed here, and a few planes that had short production runs or have been used mainly by local-service carriers.[19]

Table 4.1 is divided into three sections, according to the range of the various plane models, to correspond with a central fact of aircraft operating economics—both revenue and cost per seat-mile are extremely sensitive to the average "stage length," or "length of hop." A very short flight mainly consists of expensive take-off and landing operations, with a slow average speed, whereas a long flight amortizes the take-off and landing over a multihour flight segment at cruising speed. Thus every comparison in table 4.1 represents an attempt to compare the revenue and operating costs of planes flying the same stage length, in order to hold constant this crucial operating variable.

Our basic unit of measurement—the characteristic x in the above theoretical discussion—is an aircraft's ability to produce "available seat-miles per unit of time." Three basic figures are estimated in table 4.1 for the two planes in each comparison—total annual available seat-miles (asm), revenue per seat-mile, and cost per seat-mile. To control for the varying routes and operating practices of the airlines using each plane, annual utilization (col. 2) is held constant for each pair of planes, and speed is held constant when both planes in a comparison are jets. The number of seats, of course, is allowed to vary, since this is a major determinant of the differing productivity of the various plane types. The product of columns 2, 3, and 4, is annual available seat-miles (col. 10).

The fifth column displays the average stage length used for the calculation of revenue and operating costs. In the comparisons designated by the superscript "b," the actual recorded stage length of the second-listed ("newer") plane is chosen, and published cost curves are used to adjust the operating costs of the first-listed plane. For the comparisons designated by the superscript "e," arbitrary stage lengths of 250, 500, or 750 miles are employed to allow the use of the careful comparative study of Straszheim (1969), which provides a detailed cost breakdown of several major plane types for these standard stage lengths. In all comparisons the revenue figures refer to the particular year and stage length selected, with column 6 recording gross revenue per revenue passenger-mile, and column 7 recording revenue per available seat-mile after deducting from revenue the "overhead" costs of aircraft and traffic service, sales, reservations, advertising, administrative, and depreciation of nonflight equipment.

The measurement of revenue for a particular stage length and year in column 6 must be handled with extreme care. Published fares overstate the true revenue received by the airline, because of various categories of discounts that are available. Further, each aircraft, stage length, and year differs in the fraction of first-class and coach traffic carried. The method of revenue estimation employed in the construction of table 4.1 takes as its point of departure a yield curve of 1971 constructed by Douglas and Miller (1974, p. 90) that is adjusted for the incidence of discount fares. Then the revenue yield for earlier years is based on changes in observed average first-class and coach yields, adjusted for changes in the slope of the yield curve (over time the price of short-haul flights has increased substantially relative to long-haul flights). The mix of first-class and coach fares is available for each plane separately from CAB records.

The aircraft operating cost figures in column 8 exclude all capital costs, since our basic formula calls for the calculation of net revenue available to "cover" capital costs. The major categories of operating cost included are flight crew wages, fuel, insurance, and aircraft maintenance expenses. The operating cost estimates marked with the superscript "b" are based on the actual recorded experience of the U.S. domestic trunk airlines, with the costs of the first-listed plane type adjusted to correspond to the stage length of the second-listed plane type (thus the costs of the second-listed plane type are those actually recorded in CAB records). The operating cost estimates marked with the superscript "e" are based on Straszheim's comparisons, in some cases adjusted for wage changes between Straszheim's year of study (1969) and the comparison year.

Finally, adjusted revenue minus operating cost provides an estimate of net revenue per available seat-mile (col. 9), and this figure times annual seat-miles provides the basic computation of annual net revenue, needed for the comparison in equation (32) with the price of each plane type. We note that table 4.1 makes each pairwise comparison for a single year, thus holding constant output prices and the prices of operating inputs, particularly fuel and the wages of flight crews and maintenance labor. The plane that appears to have provided the highest level of net revenue per available seat mile is the short-range Douglas DC-9-30, while the highest absolute level of net revenue is provided by the largest plane, the Boeing 747.

Table 4.2 combines these net revenue estimates with data on the sales price of the various plane types to allow computation of the quality adjustments using equation (31) developed above. The prices are the same as those used in the development of the price index for identical models displayed as the lower solid line in figure 4.6. In most cases the "old" and "new" models being compared were not actually constructed simultaneously, requiring the adjustment of the "old price" for changes in the price of identical models between the year of its disappearance and the first sales year of the new model. In this way the sales prices of the two planes in each comparison are computed for the same year, thus allowing the price of output and operating inputs to be held constant.

One indication of the enormous profitability of the jet planes, compared to the piston planes they replaced, is given in column 5, which shows the ratio of net revenue in the comparison year to the replacement price of the plane in the same year. Because most airlines depreciated their piston planes over short seven- or eight-year intervals, it is apparent that the DC-7B and the Convair 400 barely covered depreciation expense, much less any interest cost or allowance for profit. On the other hand, some of the jets appear to have been extremely profitable, especially the "stretched" long-range DC-8-61 and short-range DC-9-30.

An interesting pattern in column 5 is the deteriorating profitability of a given model over its lifetime. For instance, the n/v ratio for the DC-8-61 declined from as much as .475 in 1967 (line 4) to .238 in 1972 (line 1). Similar declines occurred for the Boeing 727-100 (from .225 in 1963 to .173 in 1968), the Lockheed Electra L-188 (from .388 in 1959 to .243 in 1963), and DC-9-10 (from .340 in 1965 to .314 in 1967). This pattern makes sense if new models are continually introduced and allow the reduction of average operating costs and fares, while the costs of operating any given model are driven up by rising wages.

As discussed above, these estimates of the quality adjustment factor require an assumption to be made regarding the curvature of the function linking the price of the aircraft to their capability of earning net revenue, holding technology constant. There appears to be no direct way of estimating this function by examining the cross-section of planes built at any given time, because the planes built in the long-range, medium-range, and short-run categories are really separate products that defy comparisons. Further, at any given time, typically only the most advanced plane in each category is constructed. In lieu of any direct evidence on the curvature of the $v(n, \sigma)$ function, the curvature parameter has been assigned a value of 1.2 in table 4.2, implying diminishing returns in the provision of net revenue from increases in aircraft size (the assumed elasticity of net revenue to increases in cost is $1/1.2 = .833$). The resulting correction factor for curvature is listed in column 8; if the assumption of diminishing returns is incorrect, then the real price reductions in column (9) would be smaller. On the other hand, if the "true" function were to have a greater degree of curvature, then the real price reductions would be correspondingly greater.

Ironically the first comparison between the "stretched" DC-8-61, manufactured during 1966–69 and in continued use today, indicates that the introduction of the controversial wide-bodied DC-10-10 represented a "quality deterioration," in the sense that the price of the new model increased substantially more than the net revenue it was capable of providing. Thus the quality adjustment formula indicates a "real" price increase of 10.8%. All of the other comparisons indicate a quality improvement in the transition from the old to the new model, requiring the downward adjustment in the inflation rate recorded by the CAB index recording the change in prices of identical models.

It is not surprising that the largest indicated quality adjustments in column 9 are for two piston planes, the DC-7B and Convair 440. A considerably smaller adjustment is indicated for the transition from the medium-range DC-6B to the turboprop Lockheed Electra (L-188). It is well-known that the DC-7 series was a particularly inefficient airplane, representing the ultimate level of resources that could be usefully employed, given the obsolete piston-engine technology. The DC-7 may well have been incapable of making a profit at the time of the introduction of jets in 1959, only six years after the first commercial flight of the DC-7 in 1953; this interpretation is consistent with the precipitous decline in the prices of used long-range aircraft during the period 1958–62.

Among the other transitions between models documented in table 4.2, we note that the medium-range piston DC-6B, although not as inefficient relative to subsequent aircraft as the DC-7 and Convair 440, nevertheless was much less efficient than the "transition" turboprop Lockheed Electra. Further, the Boeing 727-100 represented very little further technological improvement over the Lockheed Electra, at least from the point of view of the airline operators; thus the subsequent disappearance of the Electras must at least partially reflect the favorable verdict of passengers regarding the speed and comfort of the Boeing 727.

We note that the transition from the first-generation to second-generation jets has resulted in efficiency improvements that in some cases are almost as important as the earlier transition from the pistons to turboprops and first-generation jets. Particularly important was the "stretching" of the DC-8, DC-9, and Boeing 727, yielding roughly a doubling of net revenue at only 10%–25% additional resource cost. In contrast, the shift to the wide-bodied DC-10 and 747 does not appear to have represented a major breakthrough in operating efficiency, and this fact is reflected below in the failure of our aggregate quality adjustment for aircraft to exhibit a major decline in the final 1970–71 transition period.

4.4.4 A New Deflator for Commercial Aircraft

The changes in "real" price in column 9 of table 4.2 can be used to create adjustment factors for each aircraft included in the comparisons. Because the current national income accounts deflator uses 1972 as its base year, the aircraft produced in that year are treated as having adjustment factors of 1.00. These planes include the long-range DC-10-10, the Boeing 747, the "stretched" Boeing 727-200, and the "stretched" DC-9-30. Then earlier planes are attributed quality relatives based on the change in "real" price in column 9 of table 4.2 between them and their successors.

How should these "quality relatives" for individual planes be combined into a "real" price-change index to be combined (as in eq. [33]) with the existing index of price change for identical models? First, prices and numbers of units sold were obtained for every important type of plane produced by U.S. commercial aircraft manufacturers and sold to U.S. airlines (both domestic and international) during 1946–78.[20] Then a method had to be devised for weighting together the changes in the "real" price index for individual planes when a transition was made from an old model to a newer model. Neither the conventional Paasche nor Laspeyres methods could be used to weight the relatives, since there were no years when all of the planes in a given group (long-, medium-, or short-range) were manufactured simultaneously. Instead, a variant on the Divisia index method was employed. Changes in quality relatives from one plane to a succeeding model were not weighted by sales in the transition year, because often sales of a discontinued model in its last year, or sales of a new model in its first year, were too small to properly represent the importance of the particular plane. Instead, the weights for planes involved in the transitions were based on their nominal sales during time intervals spanning periods when a particular group of planes was manufactured simultaneously. As an example, in the long-range group the transition in 1969–71 between the DC-8-61, and Boeing 707-100 and 707-300, on the one hand, and the Douglas DC-10-10 and Boeing 747, on the other hand, was handled by weighting changes in quality relatives between the individual old and new models by sales of each of the three old models during the entire 1966–69 period when they were all manufactured simultaneously. The resulting average change in the quality relative was phased in partially in 1970 (when the B747 was first delivered) and partially in 1971 (when the DC-10 was first delivered), with the weight on each year in proportion to the relative sales of the two new models in the 1970–75 interval.

The resulting indexes of changes in the quality relatives for the three major groups of planes were in turn weighted together to form an aggregate index of these changes, using as weights the nominal sales of each group in the three years surrounding the change.[21] These methods of weighting help to smooth out the final index and protect it from spurious changes due simply to the fluctuating nominal sales of different types of planes. Any index based on weighting the *levels* of the quality relatives by current year sales, as opposed to weighting *changes* in the quality relatives by sales over an interval, tends to give the appearance of marked year-to-year fluctuations in quality that in fact did not occur.

Table 4.3 and figure 4.6 illustrate the final index that results from these calculations. In table 4.3 the two sources for the current official national income accounts deflator for aircraft are shown in columns 1 and 2, and our new index for identical models purchased by identical airlines is displayed in column 3. The aggregate index of the weighted average of changes in the quality relatives is added together with the changes in column 3 for 1946–57 and 1977–78 and column 1 for 1957–77, as in equation (33) above. When the resulting sum of previously unmeasured quality change (dp^x/p^x) and the price change of identical models (dC/C) is added together to create the nominal input price-change index (dP^x/P^x), we obtain the index displayed in column 4. The timing of the newly measured quality change is apparent in column 5, which displays the ratio of the new index based on equation (33) to the existing CAB index from column 1.

As might have been expected, the most dramatic drop in the average adjustment factor in column 5 occurred in 1957–60, as a result of the replacement of the piston DC-6 and DC-7 series by the turboprop Lockheed Electra and pure jet Boeing 707 and 720, and the Douglas DC-8. Then the average adjustment factor remains essentially constant until

1966, when the first of the short-range DC-9-10 aircraft was phased in. Further rapid reductions occur in 1967–69, when the "stretched" second-generation jets replaced their earlier counterparts. Only a relatively small reduction in the adjustment factor is recorded in 1969–71, when the transition to the wide-bodied DC-10 and Boeing 747 occurred.

4.4.5 Possible Biases in the New Index: Evidence from the Used Aircraft Market

The new index in column 4 of table 4.3 is radically different from the official deflator. We naturally are led to ask, Which should we believe? The official deflator, based on the prices of identical models, excludes any comparison between successive models that are not identical. Implicitly this procedure involves treating successive models as differing in quality in exact proportion to their prices (adjusted for price changes in identical models). Thus if Douglas discontinued producing the $1.6 million DC-7 in 1958 and began producing the $4.4 million DC-8 in 1959, and other identical planes sold in both years remained unchanged in price, then the official deflator treats one DC-8 as equal to 4.4/1.6 (or 2.75) DC-7s. In constrast, our index imputes a 76% reduction in price to the transition, based on the observation that the new plane yielded 7.89 times as much net revenue and on an assumption about the nonlinearity of the technology relating net revenue to price.

To choose between the indexes, we are aided by the ample data available on the prices of used aircraft. If users considered a new 1959 DC-8 to be identical to 2.75 1958 DC-7s, we should see something like that ratio between the price of the two planes on the used aircraft market. On the other hand, if our new approach is more appropriate, we should find that a DC-8 was valued at an amount equal to 10 or 11 DC-7s. The first year in which both planes were sold simultaneously on the used market was 1966, and the observed price ratio was not just 10:1 but rather 22:1.[22] In the same source the price spread between the Lockheed Electra and Douglas DC-6 is not the 1.7:1 dictated by actual prices, or the 3.5:1 indicated by our quality adjustment, but rather 7.8:1.

Scattered evidence is also available to indicate that users concurred in our evaluation of the poor operating efficiency of the first-generation jets relative to the second-generation jets. For instance, in 1971 Eastern was willing to sell a fleet of 15 Boeing 720s for $2.1 million each in order to buy the same number of Boeing 727-200 models for about $6.5 million each (note the comparison in table 4.2, line 8). At the same time Eastern was able to sell its DC-8-61 aircraft at about 90% of the purchase price, while being forced to sell Lockheed Electras at 30% of the purchase price and Convair 440 aircraft at less than 10% of the purchase price.[23]

Quite recently a reasonably comprehensive report has compared prices of used aircraft in 1977. In table 4.4 are listed the ratios of used price to the new price in the most recent comparison year as well as our "quality relatives" derived from column 9 of table 4.2. Several interesting features stand out in table 4.4. First, we note that the top-listed plane in each category has a used/new relative of about 1.38. In the case of the DC-10, where the new price refers to 1972, this used/new ratio corresponds closely to the 37% increase in the official deflator between 1972 and 1977 (table 4.3 col. 1), indicating that used and new planes are regarded as perfect substitutes. For the other top-listed planes, the new prices refer to 1968 and 1967; since the national income accounts deflator increased by about 60% between 1968 and 1977, the used market indicates that the used versions of the Boeing 727-200 and Douglas DC-9-30 were not regarded in 1977 as perfect substitutions for new planes.

There is no reason why the ratios in the two columns of table 4.4 should correspond exactly. The year of the used price quotations is later than the year of the comparisons of successive models in table 4.2; the fact that the used market undervalues the older planes in comparison to our quality relatives may simply indicate that the older planes become progressively less profitable over time. A plane that the market overvalues in relation to our comparison is the DC-9-10; the source to table 4.4 indicates that this model is relatively scarce, due to the expansion of the local-service airlines. The DC-8-61 seems to be valued by the used market as much less efficient than the DC-10-10, in contrast to our conclusion. This verdict of the market appears to stem from the fact that, according to the source for table 4.4, this model has been affected adversely by U.S. government antinoise regulations, being "one of the most difficult aircraft to hush."

Passenger comfort is another factor that may explain why the used-aircraft market tends to establish greater differentials between old and new models than our comparison. This paper explicitly avoids any attempt to attribute dollar values to the value of consumer comfort or time. Nevertheless, one reason that the new wide-bodied jets may hold their value relatively well is the greater degree of comfort they offer. The seating configurations for the DC-10-10 and Boeing 747 used in table 4.1, column 4, allow for wider seats than for the "narrow-bodied" jets. Subsequent to the date of our comparison, most U.S. airlines have added an extra row of seats to all of their wide-bodied aircraft, thus reducing seat width to the narrow-bodied standard.[24] And, of course, the greater speed and comfort of jet aircraft induced a shift of passengers in the 1958–60 transition era that inevitably had to depress the used market for piston aircraft, independent of their operating cost disadvantage.

The used-aircraft market seems to provide no evidence that our comparisons exaggerate the true quality difference among old and new models and, in fact, indicates that our comparisons may understate these differences. If we review our comparison techniques to ask whether there is any consistent tendency that might understate the differences among old and new models, our attention is drawn to the amazingly high ratios of net revenue to aircraft price arrayed in table 4.2, column 5. Imagine that the real interest rate is 3%, and assume that aircraft are depreciated over 10 years at a 10% straight-line rate (many airlines use lives of 14–18 years). Then the cost of capital would be 13%, and yet the net revenue percentages for some of the newer models in table 4.2 range as high as 50%. It is possible that the resources used in tables 4.1 and 4.2 may systematically overstate revenue or understate costs, leading to exaggerated estimates of net revenue. If this tendency were uniform, all net revenue figures would be squeezed and the older planes would be pushed closer to break-even status, thus increasing the relative net-revenue advantage of the newer models. One systematic source of bias in our estimates is imparted by our assumption that future prices and costs are assumed to be the same as in the present. This conflicts with the observed tendency of net revenue to decline over the life of a plane, as operating costs rise relative to revenue yield. A slightly different conceptual framework in which the input price index held constant discounted *expected* net revenue (over the life of the plane), rather than actual first-year net revenue, would yield narrower margins for all planes and thus increase the advantage in table 4.2 of the more profitable models.

Another important source of conservatism in our estimates is the decision to use the same utilization rates for the old and new models (see source notes to table 4.1, col. 2). The actual utilization rates for piston aircraft were uniformly lower than for jets, allowing them to earn even less net revenue than indicated in table 4.1. Similarly, revenue yields on jets were higher than on propeller aircraft during the 1959–63 period due to the imposition of a "jet surcharge" on fares, while table 4.1 conservatively assumes that the propeller models had the same revenue yield as the jets that replaced them.

4.5 Conclusion

4.5.1 Potential for Application to Other Products

My own previous research and that of others suggests that there is a considerable potential for applying the techniques developed in this paper, together with other related methods, to the construction of new price deflators for types of equipment other than commercial aircraft. Another regulated industry, the generation of electricity, creates many of the same opportunities for improved measurement as in the case of airlines, because of the detailed operating data available. A preliminary analysis (Gordon 1974) indicates that the manufacturers of generating equipment achieved improvements in operating cost during the 1947–70 period that were extremely large relative to the value of the equipment, although there was a marked deceleration in this form of technological innovation after 1962. Just as in the aircraft case, the new deflator declined markedly during the 1947–70 period, unlike the official deflator, which in the case of electric generating equipment increased by a factor of 2.5.

Another appealing field of application is the whole range of consumer durables, including appliances and automobiles. Just as the operating costs of commercial aircraft were reduced by innovations that lowered fuel consumption and real maintenance input per unit of output, so consumer appliance manufacturers have evolved new models with lower energy and maintenance requirements than their predecessors. Color television sets require less electricity and have drastically lower repair frequencies than previously. Refrigerators and air conditioners use less energy, while air conditioners have become lighter and easier to install per unit of cooling capacity.[25]

Econometricians have devoted more attention to quality changes in automobiles than in any other single product. At least two studies are now available that measure the extent of technical improvement in the level of automobile fuel consumption over time. Long ago Fisher, Griliches, and Kaysen (1962, p. 446) created an index of the fuel usage of a constant-quality 1949 automobile and found a 12.8% improvement between 1949 and 1961. Using a different methodology to hold constant the quality attributes of automobiles, Wilcox (1978) has found an improvement similar to that of Fisher, Griliches, and Kaysen for their 1949–61 period (16.2%) and a further 12.5% improvement during the 1961–68 interval. Subsequently there was a deterioration in fuel economy that Wilcox relates to federal environmental legislation.

How can the value of the savings in operating cost in the appliance and automobile examples be converted into adjustments to the official price indexes for the same goods? Since no net revenue data are available, a different approach is required. In the above analysis we asked, "How much was the change in the price of the capital good needed to yield the same net revenue?" Instead we could ask, "How much would the price of the capital good have to be reduced to yield the same saving as the present value of the observed operating cost saving involved in the shift between the old and new model?" Wilcox's paper on automobiles estimates that improved fuel efficiency during the 1949–68 period was equivalent to a 10% reduction in the price of new automobiles, enough to eliminate about one-third of the observed inflation in new automobile prices over that interval.

4.5.2 Implications for the Measurement of Output and Productivity

Since real output for an individual commodity is measured as a residual by dividing nominal product by the appropriate price index, any conclusions reached above regarding the prices of durable goods have their counterpart in symmetric conclusions regarding the real output of durable goods as well as the productivity of those industries. The new deflator developed for the aircraft industry in table 4.3, column 4, can be applied to the official national income accounts figure on nominal purchases of aircraft as producers' durable equipment to yield a new real output series. In contrast to a 1957–72 annual growth rate of the official real aircraft output series of 6.2% the new output series grows at an annual rate of 16.9%. Productivity growth in the aircraft industry would also be increased at a corresponding rate. And, while labor productivity in the airline industry would not be altered, any index of the growth of total factor productivity in the airline industry would be much slower with a capital input series derived from the new deflator than with the existing official deflator. This shift of total factor productivity improvement from the airline industry to the aircraft industry makes sense, since it was the aircraft industry that invested the research and development resources to obtain the technological advances that made more modern aircraft possible (all these statements treat aircraft engine and fuselage production as occurring in a single industry).

Since this paper contains only a single detailed case study, it is impossible to determine whether aggregate official figures on real investment or real GNP are subject to minor or major revisions. The aircraft industry is so small that acceptance of our new deflator would raise the 1957–72 growth rate of real producers' durable equipment purchases from 4.52% only to 4.63% per annum. Any major impact on real investment data, not to mention real GNP data, would require a finding that corrections for nonproportional quality change apply to a broad range of industries. Thus a conclusion regarding the importance of potential revisions must await a more comprehensive study.[26]

While we are not yet in a position to assess the aggregate quantitative significance of the new measurement techniques proposed in this paper, nevertheless it is apparent from the aircraft example that the potential for revision in the official deflators for durable goods may be considerably greater than from the first round in the 1960s of econometric studies using the hedonic regression technique. Because improvements in operating efficiency by definition occur for durable goods, but not nondurable goods or services, a more comprehensive study would presumably yield the conclusion that the price of durable goods relative to other goods has declined in comparison to the relative prices registered in the national accounts.

Critics may protest that the process of correcting for changes in operating efficiency is inevitably so subjective that the resulting deflators have a wide margin of error. The detailed analysis of the airline case does indeed confirm that the estimation requires numerous steps, any one of which might be wrong, and also requires an arbitrary assumption about the shape of the function linking aircraft net revenue to capital cost. In contrast to our finding that the new 1972-base deflator in 1957 is about four times the official deflator, another investigator might find a ratio of three or six. Yet it would be unwise to reject the new index as subjective while clinging rigidly to the existing deflator, because the latter is based on the equally subjective evaluation that successive models of aircraft *differ in quality in exact proportion to observed differences in price.* Among the many pieces of evidence that deny the validity of this assumption is the observed behavior of the prices of used aircraft. In fact, the existing national income accounts are riddled with subjective decisions, including the continuing adherence to the procedure of setting permanently at unity the price index for producer purchases of electronic computers.

Finally, it must be recognized that any attempt to correct durable goods prices for changes in operating efficiency requires acceptance of the production separability assumption outlined at the beginning of Section 4.3. It must be assumed that improvements in fuel efficiency are achieved by manufacturers of the durable good and not by their users. Yet *some* assumptions are required to perform any kind of measurement work, and the most crucial assumptions employed in this paper can be validated by various pieces of outside evidence. Berndt and Wood (1975) provide evidence to support the separability assumption. The notion that users care about operating efficiency seems to be validated by the behavior of prices in the used aircraft market, not to mention the response of the prices of various types of used automobile models to changes in the price of gasoline. Similarly, the verdict that electronic computer prices should be based on prices per unit of computer service, and not on the production price per computer, is validated by the rush of users to shift to new-model computers with higher performance/price ratios. It may now be appropriate for critics to drop the accusation that new techniques of measurement are inherently subjective and to admit that the limited scope of quality adjustments in the present official deflators for durable goods conflicts with ample evidence that real-world users place a positive value on improvements in performance and operating efficiency.

Table 4.1 **Basic Revenue and Operating Cost Data for U.S. Aircraft Efficiency Analysis**

Comparison and Year	(1) Plane Types	(2) Rev. Hr/Yr	(3) Speed (mph)	(4) Seats	(5) Stage Length (miles)	(6) Gross Rev./rpm	(7) Rev. after Over-head/asm	(8) Aircraft Operating Cost/asm	(9) Cols. 7–8	(10) Annual asm's	(11) Annual Net Revenue ($million)
					Long Range						
1. 1972	DC–8–61	3073	463	175.0	942[a]	.0682	.0176	.0093[a]	.0083	249	2.067
	DC–10–10	2836[b]	483[b]	224.6	1067	.0682	.0176	.0082	.0094	320	3.008
2. 1972	B707–300B	3457	485	143.0	1429[a]	.0601	.0169	.0106[a]	.0063	240	1.512
	B747–100	3146[b]	507[b]	317.1	1962	.0601	.0169	.0087	.0082	532	4.362
3. 1967	B707–100B	3599	489	124.6	1166[a]	.0546	.0159	.0094[a]	.0065	219	1.424
	DC–8–61	3990[b]	485[b]	195.5	1223	.0546	.0159	.0070	.0089	344	3.062
4. 1967	DC–8–50	3836	479	130.7	873[a]	.0546	.0164	.0086[a]	.0078	240	1.872
	DC–8–61	3990[b]	485[b]	195.5	1223	.0546	.0164	.0070	.0094	359	3.375
5. 1959	DC–7B	[c]	248[d]	79.1[c]	750[e]	.0590	.0207	.0172[e]	.0035	65	0.228
	DC–8–50	3325[c]	410[d]	120.8[c]	750[e]	.0590	.0207	.0098[e]	.0109	165	1.799
6. 1959	DC–7B	[c]	248[d]	79.1[c]	750[e]	.0590	.0207	.0172[e]	.0035	60	0.210
	B707–100B	3084[c]	410[d]	121.9[c]	750[e]	.0590	.0207	.0098[e]	.0109	154	1.679
					Medium Range						
7. 1971	B727–100	2537	433	96.2	556[a]	.0797	.0242	.0149[a]	.0093	106	0.986
	B727–200	2610[b]	429[b]	124.3	518	.0797	.0242	.0110	.0132	137	1.808
8. 1971	B720	2576	451	116.6	847[a]	.0797	.0242	.0169[a]	.0073	135	0.986
	B727–200	2610[b]	429[b]	124.3	518	.0797	.0242	.0110	.0132	144	1.901
9. 1963	L–188	2409[c]	290[d]	75.1	500[e]	.0718	.0218	.0134[e]	.0084	52	0.437
	B727–100	[c]	376[d]	96.2	500[e]	.0718	.0218	.0117[e]	.0101	87	0.878
10. 1959	DC–6B	[c]	216[d]	65.5[c]	500[e]	.0708	.0248	.0176[e]	.0073	34	0.248
	L–188	2409[c]	290[d]	75.1[c]	500[e]	.0708	.0248	.0121[e]	.0127	52	0.660

Table 4.1 (continued)

Comparison and Year	(1) Plane Types	(2) Rev. Hr/Yr	(3) Speed (mph)	(4) Seats	(5) Stage Length (miles)	(6) Gross Rev./ rpm	(7) Rev. after Over-head/ asm	(8) Aircraft Operating Cost/ asm	(9) Cols. 7–8	(10) Annual asm's	(11) Annual Net Revenue ($million)
					Short Range						
11. 1967	DC–9–10	2621	378	66.6	280[a]	.0831	.0290	.0157[a]	.0173	66	0.878
	DC–9–30	2047[b]	348[b]	97.4	257	.0831	.0290	.0117	.0173	96	1.660
12. 1965	CV–440	[c]	165[d]	43.7	250[e]	.0848	.0296	.0242[e]	.0048	19	0.091
	DC–9–10	2621[c]	375[d]	66.6	250[e]	.0848	.0296	.0155[e]	.0141	65	0.917

Source by col.:

(2) Revenue hours per year. From United States Civil Aeronautics Board, *Aircraft Operating Cost and Performance Report* for the year in question (U.S. Federal Aviation Agency for 1963 and prior years). No figures are shown for piston planes, which are allocated the same utilization as the jet plane used in each comparison.

(3) Speed. All comparisons except those marked with superscript "d" are from the same sources as col. (2). Those marked with superscript "d" are from Straszheim (1969, p. 76).

(4) Seats. All comparisons are from the same sources as col. (2). For those marked with superscript "c," figures from the 1963 FAA document were used for 1959 as well.

(5) Stage length. All comparisons except those marked with superscript "e" are from the same sources as col. (2). For those marked with superscript "e," operating cost comparisons are taken from Straszheim (1969, p. 86) for the stage lengths indicated.

(6) Fare data are based on a yield curve adjusted for discounts displayed in Douglas and Miller (1974, p. 90). For earlier years, e.g., 1967, the 1971 data are multiplied by the following three ratios that, when multiplied together, adjust for the changing role of discounts and the gradually changing tilt of the yield curve: (*a*) the ratio of the 1967 to the 1971 published fare for the stage length in question, from the *Official Airline Guide*; (*b*) the ratio of the 1971 to the 1967 published coach fare for the 740-mile stage length; (*c*) the ratio of the 1967 coach yield to the 1971 coach yield, from the CAB *Handbook of Airline Statistics* (1973). First-class fare data are calculated by the same procedure independently and are weighted together with coach data using the ratio of first-class to coach-class revenue passenger miles for each year, from the *Handbook of Airline Statistics*.

(7) Gross revenue data are multiplied by two ratios to provide figures on net revenue attributable to a given aircraft per available seat mile: (*a*) load factor for the given plane in the given year, from the same sources used for col. (2);(*b*) the ratio of direct cost to total cost, taken as a percentage (57.2) of the direct cost categories (flying operations, maintenance, depreciation, and capital costs) to total costs (also including aircraft and traffic servicing, passenger service, promotion and sales, general administrative, and depreciation of nonflight equipment), as given for the year ending June 30, 1971, in Douglas and Miller (1974, table 2-1, p. 8).

(8) Except for comparisons designated by the superscript "e," cost figures (including flying operations and maintenance but excluding depreciation) were taken from the source of col. (2). Comparisons designated by superscript "e" were taken from Straszheim (1969, pp. 249–51), where the figures shown from 1965 were adjusted to the year shown by multiplying crew wages and maintenance expense by the ratio between the earlier year and 1965 of the BLS economy-wide nonagricultural average hourly earnings index.

(9) Col. (7) minus col. (8).

(10) Cols. (2) times (3) times (4) (expressed in millions of asm's per plane-year).

(11) Cols. (9) times (10).

Note: asm = available seat mile.

[a] Cost per asm was calculated using the stage length of the other plane in the comparison, adjusting the stage length shown for this plane by the cost curves illustrated in Straszheim (1969, p. 86).

[b] Annual asm's (col. 10) were calculated by using figures in cols. (2) and (3) for the other plane in the comparison.

[c] Seat totals used for 1950 are those listed for the particular plane in the USFAA volume for 1963.

[d] Speeds shown for the relevant stage length in Straszheim (1969, p. 76).

[e] Costs per asm adjusted from 1965 figures listed in Straszheim (1969, pp. 249–51) using the BLS average hourly earnings index for the nonfarm private economy.

Table 4.2 Comparisons of Purchase Price and Net Revenue for U.S. Aircraft Efficiency Analysis

Comparison and Year	(1) Plane Types	(2) Original Price (Year)	(3) Price in Comp. Year	(4) Net Rev. in Comp. Year	(5) n_t/v_t	(6) v_{1t}/v_{0t}	(7) n_{1t}/n_{0t}	(8) $\left(\frac{n_0}{n_1}\right)^{.2}$	(9) $\Delta p^x/p^x = (6) \times (8) \div (7) - 1$
Long Range									
1. 1972	DC–8–61	7.7 (1969)	8.7	2.067	.238	1.736	1.455	.928	.108
	DC–10–10		15.1	3.008	.199				
2. 1972	B707–300B	6.7 (1968)	7.5	1.512	.202	2.627	2.885	.809	−.263
	B747–100		19.7	4.363	.221				
3. 1967	B707–100B	5.7 (1967)	5.7	1.424	.249	1.245	2.150	.858	−.503
	DC–8–61		7.1	3.062	.431				
4. 1967	DC–8–50	5.4 (1966)	5.6	1.872	.334	1.268	1.803	.889	−.375
	DC–8–61		7.1	3.375	.475				
5. 1959	DC–7B	1.6 (1958)	1.6	0.228	.143	2.750	7.890	.662	−.769
	DC–8–50		4.4	1.799	.409				
6. 1959	DC–7B	1.6 (1958)	1.6	0.210	.131	2.875	7.995	.660	−.762
	B707–100B		4.6	1.679	.365				

Medium Range									
7. 1968	B727–100 B727–200	4.6 (1968)	4.6	0.794 5.2	.173 1.455	1.130 .280	1.832	.886	-.453
8. 1968	B720 B727–200	3.7 (1961)	4.4	0.794 5.2	.180 1.530	1.182 .294	1.927	.877	-.462
9. 1963	L–188 B727–100	1.7 (1959)	1.8	0.437 3.9	.243 0.878	2.167 .225	2.009	.870	-.062
10. 1959	DC–6B L–188	1.1 (1958)	1.1	0.248 1.7	.225 0.660	1.545 .388	2.661	.822	-.523
Short Range									
11. 1967	DC–9–10 DC–9–30	2.7 (1966)	2.8	0.878 3.1	.314 1.660	1.107 .535	1.891	.880	-.485
12. 1965	CV–440 DC–9–10	0.6 (1957)	.65	0.091 2.7	.140 0.917	4.154 .340	10.077	.630	-.740

Source by col.:

(2) USCAB form 41; 1967 and earlier observations from schedule B–43 dated December 31, 1967.

(3) Price in col. (2) for the first plane listed is multiplied by the change between the year shown in col. (2) and the year of the comparison of the CAB price index shown in table 4.3, col. (1). The price for the second-listed plane in each comparison is obtained for the comparison year from the same source as is listed in col. (2).

(4) Table 4.1, col. (11).

(5) Col. (4) divided by col. (3).

(6) The ratio of price in col. (3) for the second-listed plane to the price in col. (3) for the first-listed plane.

(7) The ratio of the net revenue listed in col. (4) for the second-listed plane to the net revenue listed in col. (4) for the first-listed plane.

(8) The inverse of col. (7), raised to the .2 power.

(9) Cols. (6) times (8) divided by (7) minus 1.0.

Table 4.3 **Alternative Price Indexes for Commercial Aircraft, 1946–1978 (1972 = 100)**

Year	(1) CAB Index	(2) BEA Extrapolation	(3) New Index for Identical Models	(4) New Index Based on Eq. (33)	(5) Cols. (4) ÷ (1)
1946		36.8	48.0	196.3	
1947		41.9	48.0	196.3	
1948		44.7	48.0	196.3	
1949		46.5	54.4	222.8	
1950		49.0	60.9	249.3	
1951		55.9	60.9	249.3	
1952		55.6	60.9	249.3	
1953		56.8	66.5	272.5	
1954		57.5	68.3	279.8	
1955		59.8	69.0	282.6	
1956		65.2	70.1	287.2	
1957	68.5		70.4	288.1	4.206
1958	69.6		70.4	259.3	3.726
1959	72.1		70.4	133.0	1.845
1960	72.3		70.4	128.1	1.772
1961	73.2		70.4	128.6	1.757
1962	75.5		68.8	132.6	1.756
1963	78.7		75.6	136.9	1.740
1964	77.1		75.6	134.2	1.740
1965	78.7		77.8	137.1	1.740
1966	80.0		78.6	119.9	1.499
1967	83.0		81.0	116.4	1.402
1968	85.6		84.2	106.0	1.238
1969	88.7		88.7	105.4	1.188
1970	94.0		94.0	103.4	1.110
1971	98.1		98.9	98.1	1.000
1972	100.0		100.0	100.0	1.000
1973	103.6		106.0	103.6	1.000
1974	108.5		109.0	108.5	1.000
1975	118.4		119.5	118.4	1.000
1976	129.3		122.1	129.3	1.000
1977	136.9		137.7	136.9	1.000
1978			151.2	150.3	

Source by col.:
(1) and (2) CAB (1977).
(3) and (4) See table 4.2 and text explanation.

Table 4.4 **Comparison of Used/New Price Ratios and Quality Relatives for Commercial Aircraft (1977)**

Aircraft	(1) Used/New	(2) Quality Relative
Long Range		
DC–10–10	1.39	1.00
Boeing 747–100	1.19	1.00
DC–8–61	.67	1.11
Boeing 707–300B	.51	.74
Boeing 707–100B	.35	.55
DC–8–50	.31	.69
Medium Range		
Boeing 727–200	1.38	1.00
Boeing 727–100	.65	.54
Boeing 720B	.27	.54
Lockheed L–188	.23	.51
Short Range		
DC–9–30	1.37	1.00
DC–9–10	.82	.52
Convair 440	.08	.13

Source by col.:
(1) The used price is from Sweetman (1977). The new price is the second price shown for each aircraft in col. (3) of table 4.2.
(2) Based on table 4.2, col. (9).

Notes

1. For a general review of the central issues involved in the measurement of real output for productivity analysis, see the Panel to Review Productivity Statistics (1979, chap. 5).

2. The Denison criterion is also addressed in the debate between Denison (1969; 1972) and Jorgenson and Griliches (1967, 1972).

3. See Gordon (1971*a*, 1974).

4. This criticism was first made in Gordon (1971*b*).

5. In some applications involving departures from free competition, e.g., smog control devices, the two criteria do yield different measures. This paper is entirely concerned with examples in which choices of quality characteristics are made freely by business firms.

6. The assumption of costs that are constant in quantities, but increasing in quality characteristics, has been adopted by most previous papers in this literature, including Parks (1974) and Rosen (1974).

7. The vector of output characteristics (y) might be imagined to consist of m-1 homogeneous goods, plus an "mth" good having n separate characteristics: $y = (y_1, y_2, \ldots, y_{m-1}, y_{m1} y_{m2}, \ldots, y_{mn})$. Now quality change involves an increase in one of the characteristics of the "mth" good. If resources and technology are fixed, this would in turn require a reduction in the output of one of the m-1 other goods.

8. Berndt and Wood (1979, p. 344), with the notation of the present paper substituted for that of the authors.

9. In what follows expected future values of the exogenous parameters are implicitly assumed to remain equal to their current values.

10. If the firm maximizes profit, which consists of net revenue less the user cost of its capital stock of durable input characteristics, it must be operating on the upward sloping segment of the net revenue function. This is evident in fig. 4.5 below.

11. During the two-decade period 1953–72, the nominal price of gasoline in the Consumer Price Index (CPI) increased 34% compared to 56% for the all-items CPI, representing a reduction in the relative price of 14.4%.

12. The depreciation rate should depend both on the built-in durability characteristics of the good and the user-chosen intensity of repair and maintenance services. In the simple version of the model considered here, with only a single composite operating cost characteristic, the depreciation rate is assumed to be fixed.

13. For some qualifications, see Muellbauer (1974).

14. Imagine that point B lies along an extension of the ray OA. Then the new level of net revenue per dollar of capital ($V_1 B / O V_1$) would be the same as before ($V_0 A / O V_0$). Since the percentage user cost per dollar of capital ($r + \delta$) is constant, the rate of return on capital would remain constant.

15. Among the most important are Griliches's (1971) notes on technical problems in the hedonic literature, and the debate between Gordon (1971*a*, 1974) and Triplett (1976) on the extent of a significant quality bias in existing official price indexes.

16. This description is based on the United States Civil Aeronautics Board (1977). This document was kindly provided to me by Don Eldridge of the Bureau of Economic Analysis.

17. To minimize the burden of copying the required data, prices for all planes during 1968–78 were based on form 41 dated December 31, 1978, and during 1946–67 were based on schedule B-43 dated December 31, 1977. Data for the following sample of airlines were collected: American, Braniff, Delta, Eastern, TWA, United. Price quotations were obtained for 802 separate aircraft from the 1978 form, for 767 aircraft from the 1967 sheet.

18. Prior to 1957 the official deflator is based on a weighted average of the Producer Price Index component indexes for diesel engines, fabricated metal products, metalworking machinery, and electrical machinery. None of these indexes contains any components manufactured by the aircraft industry.

19. More specifically, the excluded Lockheed L-1011 duplicates the Douglas DC-10; the Convair 880 and 990 were high-cost jets that had short production runs and were phased out by their main users by the end of the 1960s; the short-range piston Martin 404 mirrors the performance of the Convair 440; and the Lockheed "Constellation" series (749, 1049, 1649) duplicates the Douglas DC-6, DC-6B, and DC-7 series.

20. Major sources are Avmark (1976, and earlier issues) and Douglas Aircraft annual reports.

21. If a change between models occurred in a group, say long-range aircraft, between 1969 and 1970, this change was weighted together with the changes recorded for the two other groups (medium- and short-range) using the nominal sales in the respective groups in 1969, 1970, and 1971.

22. The source is Aircraft Exchange and Services, Inc., (1966, p. 1). The average price quotation on the two DC-8-30s listed is $4,000,000, and of the nine DC-7s listed $183,000. Of course the DC-7s were somewhat older, being manufactured between 1953 and 1959, but this age difference cannot account for the price spread.

23. These price quotations are all from Watkins (1971).

24. In 1979 the average seat width on United's DC-8 aircraft was 16.89 inches and on its 747 and DC-10 aircraft 17.00 inches, from United brochure "Great Seats in the Friendly Skies."

25. Some crude adjustments to the prices of consumer appliances for savings in operating costs are contained in Gordon (1974, chap. 6).

26. This study is underway. The draft monograph (Gordon 1974) is under revision to update the figures, to incorporate the measurement techniques discussed in this paper, as well as other improvements suggested by reviewers and critics.

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Comment

Jack E. Triplett

In the section dealing with Input and Output Price Index Concepts, Gordon suggests that we have reached substantial agreement on the major issue: quality change should be accounted for by user value in input price measures, but by a resource-cost rule for output price indexes. Yet, in subsequent sections exploring what he refers to as "nonproportional quality change," he presents an alternative that would be employed for *both* input and output price measures. Actually, it corresponds closely to one method currently used by the Bureau of Labor Statistics (BLS)—the use of manufacturers' cost data to make quality adjustments for some kinds of durable goods.

In this comment, I first describe briefly the BLS use of cost data for making quality adjustments and the rationale that has been used to justify it. The other sections address aspects of Gordon's paper.

What Does the BLS Do and Why Does It Do It?

It is well known that the BLS uses manufacturers' cost data to adjust prices of some goods for quality changes. This is documented for the Producer Price Index (PPI) in the Early and Sinclair paper in this volume. New cars are also handled this way in the Consumer Price Index (CPI), as are federal safety standards for a few other products.

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It is important to emphasize that use of manufacturers' cost data is not the only method for handling quality change in the indexes and is not necessarily even the preferred way of treating quality change. If equilibrium selling prices of new and old varieties were available in the same situation or time, one could link the index over from old to new varieties; in this case, the price ratio between the two becomes the implicit quality adjustment. If equilibrium price data are not available (and as Early and Sinclair note, they seldom are) an appropriate alternative for *input* price indexes would be measures of user value for the two varieties, again taken for the same situation. Gordon and I, as well as official BLS policy, all agree on this.

Still considering input price indexes, what is done if neither equilibrium price relatives nor user-value information is available? In practice, a quality change may be handled in one of several ways.

1. When there are no data available for making an *explicit* quality adjustment (the majority of cases), one of two options is employed.

a) Where quality change is deemed "small" (according to procedures adopted on a product-by-product basis) it is neglected.[1] This leads to the so-called direct price comparison, which means that all of the observed price change will be recorded as pure price change, with no allowance for quality change. The usual presumption is that quality changes are on balance improvements; if so, direct comparison imparts an upward bias to the indexes.

b) On the other hand, if the BLS finds that the quality change is greater than the cut-off value and so therefore cannot be ignored, this leads to one of two forms of "linking" procedure. The procedure used in the PPI takes the entire price differential between the new and old varieties as the measure of quality change.[2] Obviously, when all of the observed price differential is counted as quality change, the BLS misses any price change that may have accompanied the introduction of a changed item. The error could in principle go in either direction. If price changes are more likely to be made when new models are introduced, during an inflationary period the PPI linking procedure would tend to produce a downward error in the indexes; this downward error will occur regardless of whether quality changes are improvements or deteriorations. This reasoning depends on the presumption that producers try to "mask" price increases by coupling them with new model introductions, which may not be true even in inflationary times, and is even less likely when prices are falling.[3]

2. In some cases, the BLS obtains the cost of the quality change from the manufacturer who provides the price data to the BLS and uses cost as an explicit quality adjustment. The actual process involves two steps.

a) The first is a rule or criterion for judging whether or not a particular change in specifications reported by the manufacturer is or is not to be accepted as a quality change for the purposes of the index. The criterion used depends explicitly on whether the BLS index is interpreted as an input price index or as an output price index. In practice, both CPI and PPI indexes have been treated as if they were input price indexes; for input price indexes the quality criterion is user value.

As an example of the operation of the quality criterion, several years ago an auto manufacturer submitted as quality improvements a change from conventional to digital clock faces and a redesigned speedometer which did not register extremely high speeds. Both were disallowed because the BLS commodity specialist judged that neither change represented increased transportation value to the user of the automobile.[4]

b) If it is determined that a specification change does represent increased or decreased value to the user, the second step is to *estimate* that value. Using resource-cost data to estimate user value rests on the principle that in equilibrium the marginal cost of any change will approximate its incremental value to the user. Where manufacturers' cost data are used as quality adjustments in a BLS index that is interpreted as an input price index, they are explicitly regarded as an approximation to the user-value data that are considered theoretically appropriate for the index.

Thus, in using manufacturers' cost data the BLS distinguishes between the quality *criterion* and the quality adjustment *estimator*. The criterion for measuring quality change in a BLS input price index is always user value—the correct theoretical quality adjustment method for input price measures (see Sec. 5.3 of my paper in this volume). The estimator, on the other hand, is sometimes manufacturing cost because that may be the only information obtainable, and because cost should have an equilibrium relationship to the theoretical quality criterion of user value.

Any estimator may contain error, relative to the correct measurement. It happens that this particular estimator has some unique problems. One manifestation is the occasional manufacturer's report of increased quality at reduced cost, an obvious case where the estimator is in error (though one should not conclude that error is absent just because cost and user-value information move in the same direction). Second, "downsizing" and other complex changes in automobiles in recent years have caused the cost-based procedure to break down at times, so that some new automobile models have been handled in both CPI and PPI by imputation to quality adjusted price movements of cars which were less drastically changed.

The preceding has concerned input price measures. Output price measures have only recently become operational. In the output price index case, the correct quality criterion would be resource cost. Manufacturers' cost data do measure that.[5] However, for this case a resource-cost rule must also be applied as a decision rule for judging whether a particular product change is a quality change. One would not employ a user-value criterion to judge whether a particular specification change should be accepted as quality change for an output price index. Thus, there is no reason for using a "mixed" quality adjustment rule for output price measures.

Hedonic techniques are an alternative method for adjusting for quality change. A full discussion of the merits and disadvantages of hedonic methods is beyond the scope of the present note (on this, see Griliches 1971). No BLS index currently incorporates hedonic quality adjustments, despite extensive internal BLS research on hedonic methods over the last decade or so. That research suggests that they are probably best suited for products where conventional specification pricing is unworkable (computers, e.g., or aircraft [see Archibald and Reece 1977, 1979]), or to solve particular pricing problems (housing prices being an example [see Gillingham 1975]), or as a check on the validity of conventional procedures (Triplett and McDonald 1977; and the Early-Sinclair article in the present volume). It is well established that hedonic methods may break down for the same reasons that conventional methods fail, with automobiles a major case in point (Triplett 1969; Ohta and Griliches 1976).

Gordon's Alternative Method

In his section on nonproportional quality change, Gordon says that "the distinction between the 'user-value' and 'production-cost' criteria for the measurement of quality change is misleading, since both are used. . . . User value is the criterion used to define . . . the characteristic desired by the user. And production cost is the criterion used to make the actual quality adjustment" (p. 214). This proposal matches almost exactly what the BLS actually does with cost-based data in input price indexes—a user-value rule for defining quality change, with resource-cost data used as an estimator. Gordon's proposal appears in conflict with the results of my paper, and with the BLS rationale for what it is doing, but does not really amount to that.[6]

To clarify the matter, consider the first two equations from my paper in this volume (Chap. 5):

$$G = G(C, K_G, L) \tag{1}$$

$$C = C(K_C, L) \tag{2}$$

The objective is to compute an input price index for, say, computers, or for computer services (C)—that is, a measure of the price paid for computers by the using industry (which I named "gadgets"). As an input price index, the computer index is one component of an index for the right-hand side of equation (1). An output price index for computers is a price index for the left-hand side of equation (2).

In my paper, the analytical technique for handling quality change in input price index numbers involves respecification of the right-hand side of equation (1), so that the input price index is defined in terms of input characteristics of computers rather than in terms of the good "computers." For output price indexes, the left-hand side of equation (2) is similarly respecified so that the "computer" variable is replaced by measures of computer output characteristics.

Essentially, respecification from goods space to characteristics space serves to transform the discussion from an argument over how to treat the computer "box" (the form the quality change literature has taken in the past) to an analysis of the properties of computers that are important in its own production function and in the production functions for using industries. However, even in characteristics space there remain two theories—input and output price indexes have separate theoretical justifications and require separate, and different, theoretical treatments of quality change (see Secs. 5.3 and 5.4 of my paper). It is a misunderstanding of the theoretical result to suppose that shifting the unit of analysis from "boxes" to the characteristics of boxes yields a single method of quality adjustment, applicable to both input and output price indexes.

Consider the input case. Any input cost index (whether in goods space or characteristics space) depends only on the using industry's technology and the costs of acquiring inputs. To implement the theoretical quality adjustment method for input price indexes discussed in Section 5.3.3 of my paper, one would collect the following information from the gadget producer: (1) the list of computer characteristics important to gadget production; (2) the production function for transforming computer characteristics and other inputs into gadgets; and (3) the costs or prices paid for all inputs, including computer characteristics.

Believing that the second and third pieces of information are probably not available from the buyer of computer services, Gordon instead proposes to collect data from the seller. This can be justified by the same rationale that motivates the BLS introduction of production-cost data into the PPI and CPI—in equilibrium the marginal manufacturing cost of a computer characteristic will approximate its incremental value when used in the production of gadgets. This, then, is the basis for Gordon's equation (4)—which was obtained by substituting the input demand functions from the using industry (here gadgets) "into the cost function of the supplying industry" (Gordon, this volume, p. 210). The same rationale underlies his input price index (computed as the ratio of two valuations of eq. [4]), and the "shift-term" analysis that culminates in an input price index for computer service characteristics that is "measured by adjusting the observed change in cost of a new model for the change in its quantity of characteristics ($x_y dy$) multiplied by the marginal cost of producing characteristics ($C_t c_x$)" (Gordon, this volume, p. 212).

The pure theory of an input cost index contains nothing on the technology of the supplying industry. Gordon's use of production cost data in an input price index is best interpreted as an empirical approximation to what is wanted in theory, exactly the rationale that motivates the BLS empirical procedures.

To be sure, a cost-reducing innovation in the computer-producing industry may be expected to reduce the cost of computations performed in the gadget industry. And an economist wants not simply to measure prices but also to analyze them. It is clearly true that a shift in the suppling industry, or an increase in demand from the using industry, will change the market prices for computers measured in computation units. But such shifts should not appear in the price index formula because that would tend to factor them out of the price measure. One wants to be sure that cost reduction in the computer-producing industry does show up as a measured reduction in the costs of computations performed in the gadget industry.

In conclusion, it is not true that the theory specifies a single treatment for quality change in both input and output price indexes. What Gordon's argument says is that under certain conditions the two theoretical quality adjustments will give similar estimates, and for this case one can use either adjustment and obtain the same result.

The "Resource-using" and "Nonproportional" Dichotomy of Quality Change

I have reservations about taxonomies of quality change. Most have not been very enlightening, primarily because they have often been constructed around examples that contained only part of the economic information needed to evaluate the cases being classified.

A "nonproportional" quality change is defined by Gordon as one "in which production cost does not change in proportion to user value" (p. 207), or as a situation where there is "a downward shift in the supply curve of user-desired characteristics" (p. 207). These two definitions can be inconsistent.

On the "supply shift" definition, a quality change from A to either B or C in figure 5.3 of my paper involves a shift in the supply schedule (F_1 to F_2), and so is classified as "nonproportional." This is similar to points A and B in Gordon's figure 4.1. On the other hand, a quality change such as B to C in my figure 5.3 implies an unshifted supply function; this change is classified as "resource using," or "proportional."

However, neither my figure 5.3 nor Gordon's figure 4.1 contains information about user value. Accordingly, one does not know whether a downward shift in the factor requirements function, F, or in Gordon's unit cost function, V, does or does not create a situation where user-value and resource-cost rules diverge. One can read from my figure 5.3 two alternative resource-cost quality adjustments, ∂L_1 and ∂L_2 (on Gordon's fig. 4.1, the latter one is equivalent to the vertical distance on the V-axis corresponding to the movement from points D to B). But the user-value measure cannot be obtained from resource-cost information, and there is therefore no way of knowing whether the user-value change corresponds to either ∂L_1 or ∂L_2.

Similarly, one cannot determine whether user-value and resource-cost rules agree solely from knowledge that the supply curve did not shift. The movement from point B to point C in my figure 5.3 might have been caused by a shift in the using industry's production function that raised the demand for characteristics. Thus, an unshifted supply curve could be consistent with deviation between resource-cost and user-value rules, creating inconsistency in Gordon's alternative definitions of "nonproportional" quality change.

What we do know is that in equilibrium the incremental value to the user of a quality change equals the increment to the cost of producing the additional characteristics. Thus, for small changes around the point of equilibrium, and on the assumption of a competitive world where functions are smooth and where government or other nonmarket forces do not intervene, one would get approximately the same values from resource-cost and user-value measures.

Shifting functions, whether on the demand or supply side, represent one case where the two quality change criteria can yield different answers. Characterizing quality change by whether the supply curve has or has not shifted may be useful for some purposes. But it is not necessarily the same thing as a situation where user-value and resource-cost quality adjustment rules diverge. Identifying the latter situation requires information on both the cost schedule for the supplying industry and the using industry's production function.

Handling Fuel-Efficiency Changes in Price Indexes

There is no question that fuel efficiency changes should be reflected in some way in a measure of the using industry's input costs, or in a measure of the consumer's consumption costs. It is not true, however, that the fuel-efficiency effect must necessarily enter into the measurement in the form of an adjustment to the price of the durable good whose fuel efficiency changed.[7] In fact, the theory of index numbers suggests just the opposite—that the theoretically appropriate method for incorporating fuel efficiency changes into the index normally involves an adjustment other than to the price of the durable good whose fuel efficiency changed.

Suppose the manufacturer of a durable good introduces a fuel-saving innovation. That is, the new product provides the same service as the old but requires less fuel to do it.

First consider the theoretical input cost index that encompasses all of the inputs used by a particular firm or industry (eqq. 4 and 4a from my paper in this volume). Recall that this index measures the change in cost between two collections of inputs—one set of inputs represents the minimum-cost method of producing a particular output level in the initial period, the other is the minimum-cost input set in the comparison period that can produce the same output level.

If a fuel-efficiency improvement occurs in the second period, then the cost of the collection of inputs necessary to produce a given output level will fall by the decrease in expenditure on fuel (net of any price increase charged for the new durable good). That is, an improvement in, say, aircraft fuel economy will be picked up in the airline industry's input cost index in the form of a decrease in quantities of fuel. No additional adjustment to the price of aircraft is necessary. The reason lies in the nature of the theoretical input cost index: the theoretical index permits quantities to adjust to find a minimum-cost combination, and the cost saving from an improvement in fuel efficiency occurs precisely from an adjustment in quantity of fuel required for a fixed amount of output. Therefore, in the total input cost index, adjusting the price of airplanes for fuel savings would double-count the effect of increased fuel efficiency, for that saving already shows up in decreased quantities of fuel purchased by airlines.

However, a measure of the total cost of all the airline's inputs is not the only relevant price index. For some purposes, it may be appropriate to ask how prices of some components of the full set of inputs are moving. One may want a price index only for the airplanes used by airlines, or a price index for producer durable equipment used as inputs to the airline industry. Pollak (1975) referred to indexes encompassing less than the full set of inputs as "subindexes."

If the objective is to produce a subindex (such as a price index for airplanes), then one must deal with the question, What subindex is justifiable in theory? Pollak (1975) distinguishes several kinds of subindexes, but the kind most relevant to the present discussion depends for its justification on the theory of separability, as applied to production functions.[8] It is convenient to approach the subindex question by reference to Gordon's treatment.

Gordon writes the production function (his eq. [18], p. 218):

$$y = y[h, k(x, e)],$$

where inputs h and e are labor and energy, respectively, and x is defined to be "performance characteristics" (which also implies that x is to be interpreted as a vector). As the notation makes clear, Gordon is discussing an *input* price index (a price index for x) and not output price indexes (which would refer to the price of y). Thus, what is wanted is a subindex of the full input-cost index for the y-industry's inputs.

Gordon cites Berndt and Wood (1975) to confirm that capital and energy may be treated as an aggregate, separable from labor, as he has written the equation. Realism, however, is not the difficulty with Gordon's use of equation (18).

The theory of separability states that the assumption made in equation (18) permits constructing a consistent index of *wages*, without worrying about capital or energy, or an index of some aggregate of capital and energy, without requiring data on labor. But equation (18) does not permit forming an index of capital goods prices, independent of energy—which is, of course, what Gordon proposes to do. For that, one would have to be able to write the vector of x's separable from e—that is, to maintain that marginal rates of substitution between aircraft characteristics (such as between speed and fuel economy) were independent of fuel usage. That is not a plausible specification at all. Gordon seems to have misunderstood what separability theory says about forming subindexes.[9]

Instead, the assumption embodied in Gordon's equation (18), and justified by Berndt and Wood's empirical work, specifies that the theoretically appropriate subindex is an index for airplanes combined with fuel. An input subindex for airplanes alone is not theoretically justifiable. Treating fuel-efficiency changes in the airplane-fuel subindex gives a result similar to the one for the overall input cost index: because the input cost subindex is defined on airplanes combined with fuel, the effect of fuel efficiency improvement is again completely accounted for by the reduction in fuel quantities. No airplane price adjustment is called for.

Thus, neither the overall input cost index nor the subindex implied by Gordon's equation (18) calls for a quality adjustment to *aircraft* prices for increases in fuel efficiency. The reason is that economic input cost indexes (whether the full index or the subindex) are ratios of *costs*; the change in cost caused by increased fuel efficiency enters the cost calculation directly in the form of reduced expenditure on fuel. No additional quality adjustment to the price of the durable good is necessary.[10] Fuel-efficiency changes pose index number problems only when the objective is to compute fixed-weight approximations to input cost indexes, such as by use of Laspeyres or Paasche formulas. For these cases, fuel is entered with a fixed weight, and no quantity adjustments occur.

Consider this problem within the context of the Consumer Price Index. The BLS now prices a durable good (cars) and also other inputs (gasoline, repairs, etc.) necessary to use the car. Because the CPI is a Laspeyres index, there are fixed expenditure weights that apply to all of these things.

Suppose manufacturers introduced more fuel-efficient cars without reducing their size or performance characteristics. Any higher price changed for a more fuel-efficient automobile is offset by a decrease in the quantities of purchased fuel.

The problem the index maker faces is that the fixed-weight index does not permit adjustment of any quantities. This realistic problem is the one that concerns Gordon. It is important to understand, however, that the theory provides no guidance. The theory of index numbers is a theory of the exact or theoretical index, and in that index fuel-efficiency adjustments to durable goods prices are not required. The problem arises in the fixed-weight index precisely because of the condition (fixed weights) by which the Laspeyres or Paasche formula differs from the true index of input costs.

One could make the argument that in the fixed-weight framework adjusting the price of the durable good for increased fuel efficiency is at least going in the right direction and is better than no adjustment at all. I would not be unsympathetic to an argument along that line.

I would strongly prefer, however, a different approach to the problem. It has long been established that a consumption measure should pertain to the services of durable goods and not to the quantities of durables purchased. In that context, the BLS would be pricing the cost per mile of a constant quality automotive service (constant quality being defined in terms of comfort, carrying capacity, and other use characteristics). If the BLS were to price the services of durable goods, then fuel efficiency changes would appear, appropriately, as simple changes in the cost of the service. In that context, they would not present themselves in the form of a "quality problem" at all (see Triplett 1971*b*). One may rationalize Gordon's empirical work on fuel efficiency as an approximation to this alternative approach. The rationalization, however, is quite different from the one that appears in his paper.

In summary, the theory of index numbers provides scant support for fuel-efficiency adjustments to the prices of durable goods, for the reason that the theoretical input price indexes (including the input cost index discussed in my paper in this volume as well as the cost-of-living index concept) already admit into the measurement adjustments in fuel quantities occasioned by increases in the fuel efficiency of durable goods. In fixed-weight indexes, quantity adjustments do not enter into the measurement. Consequently, anything done in the fixed-weight context amounts to an ad hoc procedure, quite outside index number theory, justifiable on the hope that the adjustment will go in the right direction, and is of approximately the right magnitude. That does not necessarily condemn the empirical work; measurement can sometimes be done without tight theoretical support. But the theoretical rationale for such work is not the one Gordon gives and, so far as I can determine, does not really exist.

Conclusion

These comments have been concerned exclusively with the theoretical sections of Gordon's paper, and the paper is primarily an empirical one. Because the empirical work does not stand or fall on the particular formulations used in the theoretical section, my comments are not to be interpreted as strictures on the empirical work, which can stand on its own, and should be studied and absorbed by anyone interested in the empirical side of the quality measurement question.

I am more concerned about the interpretation to be given to empirical work of this kind than I am with the numbers actually produced. To observe that most empirical work on quality change and on hedonic methods has proceeded with little or no reference to the theory of index numbers is no new insight. But it is also true that a good part of the theorizing on this subject served up to the empirical workers has been beside the point, or worse. We are a long way, as Gordon notes, from having a good empirical grasp of the magnitude of the quality problems in our economic measurements. But unless we have a better grasp of what we want to measure—that is, of the theory and the economic concepts—we will not be able to tell whether empirical work has improved the measurement.

Notes

1. The procedures imply a rule or criterion exists for specifying which product changes are to be accepted as quality changes. The criterion for this case is the same as the one stated in 2(*a*), below.

2. In comparable situations, the CPI uses a different linking procedure that implicitly imputes to the good whose quality changed the price movement of similar goods whose quality did not change. As with the PPI procedure, one expects CPI linking to impart a downward bias when prices are rising, but this presumption has not been tested empirically.

3. A more extended discussion is in Triplett (1971*a*). Empirical attempts to evaluate the PPI linking procedure are Triplett and McDonald (1977) and Early and Sinclair (in this volume). A survey of studies on quality error in price measures is contained in Triplett (1975).

4. That such judgments may sometimes be arbitrary is an unavoidable flaw with the procedure, but judgment always plays a role in the construction of price measures. The cost-based quality measures are not unique on that score.

The complexity of the role of the automobile in modern society has required some controversial interpretations of the user-value criterion. For example, in 1971 Commissioner Geoffrey Moore, responding to the recommendations of a U.S. Government Interagency Committee, decided that legally mandated changes (smog devices, safety equipment, fuel economy standards and the like) would be treated as quality changes in all BLS indexes on the grounds that Congress had made a political judgment that the value of these changes was worth their cost. The price index treatment of some of these items remains controversial, with arguments marshaled on either side, but that issue cannot be explored fully here.

5. This does not say that they always conform precisely to the theoretical resource-cost rule. For a variety of reasons the data reported may be imperfect (see Triplett 1971*a*).

6. Conversations with Prof. Gordon have been valuable in resolving points discussed in this section.

7. This question was first raised by Fisher and Shell (1972).

8. Blackorby and Russell (1978) subsequently argued that indirect separability or separability of the cost function is the appropriate starting point for constructing input price

indexes. To preserve the notation of Gordon's paper, we merely note that fact, without incorporating it.

9. On p. 242, Gordon identifies the separability assumption as having something to do with whether "improvements in fuel efficiency are achieved by manufacturers of the durable good and not by their users." Separability of a using industry's production function is simply a way of depicting technology in the using industry; it does not depend on the supplying industry's cost or production function, nor does it depend on the sector in which fuel efficiency changes originate.

10. An additional effect may occur in the input cost index for changes in usage of other inputs that may be complements or substitutes with fuel. Also, we have not explicitly considered whether increased fuel efficiency of the durable good was a response to rising fuel prices, which would of course also be included in the input cost index.

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Reply

Triplett's constructive set of comments helps to clarify the relation of my new work on energy—efficiency adjustments to the traditional literature on index numbers. Our sole remaining disagreement concerns his doubt that energy-efficiency adjustments to the prices of durable goods are useful or appropriate in input indexes. But for my area of concern, the measurement of net investment in the national income and product accounts, changes in the service price of durable goods must be decomposed to determine the portion attributable to the manufacturer of the durable goods. This is achieved by my proposed quality adjustment procedure, which leads to a price index for durables that moves in proportion to Triplett's service price when the price of fuel is held constant.

Criteria versus Estimators for Quality Change

The first half of Triplett's comment provides a correct interpretation of my framework for quality adjustments. The approach that I advocate for input cost measurement is not the pure theoretical concept that Triplett develops in his paper. As Triplett states, the pure concept would require for its implementation a set of data collected only from *purchasers* of durable goods, including details on their production functions for every product and on the prices paid for all inputs. I reject the pure concept on grounds of practicality. The collection of price data from buyers has proven feasible only in selected pilot projects (esp. Stigler and Kindahl 1970). Since the sellers' side of the market for most manufactured goods is so much more concentrated than the buyers' side, virtually all efforts to measure prices by both official agencies and outside investigators have involved the collection of data from the seller. This leads to my hybrid concept for input cost measurement. Here the quality *criterion* is user value (e.g., the characteristic valued by the computer user is its calculations rather than dimensions of the computer box); the *estimator* used to adjust computer price indexes for differences in characteristics across models is based on the seller's marginal cost. Because this distinction between the criterion and the estimator is identical to that used by the Bureau of Labor Statistics, my criticism of their price indexes does not involve a theoretical dispute but rather concentrates on sins of omission (e.g., the failure of BLS to develop a price index for computers or commercial aircraft), and on detailed procedures (e.g., the BLS decision in 1970 to treat electronic calculators as a new product rather than as a price reduction for existing desk calculators). In fact my strongest criticisms are directed not at the BLS but at the Bureau of Economic Analysis.

It is the BEA that has chosen to deflate electronic computers by a price index (always equal to 1.0) that ignores the rapidly declining price of computer calculations, and to deflate commercial aircraft by an index that ignores the improvement represented by the invention of the jet engine.

Energy Efficiency Adjustments

The main criticism in Triplett's comment concerns my proposal to adjust the price indexes of durable goods for nonproportional quality changes taking the form of improvements in energy efficiency. In preference to my approach, Triplett prefers that the input service price of durable goods be measured, for example, the flow price per unit of time of the costs of capital, fuel, and maintenance ("The BLS would be pricing the cost per mile of a constant quality automotive service"). In this comment I make a two-step argument that, first, my proposed quality adjustments lead to durable goods price indexes that move in proportion to Triplett's service price when the costs of other inputs (fuel, maintenance labor) are held constant, and, second, that these other input costs must be held constant in performing quality adjustments if our national income accounts are to make any sense.

In the case of a "proportional" quality change taking the form of an improvement in energy efficiency, neither the service price nor my durable goods price index would register any change. Consider a situation in which a change in relative prices leads a refrigerator producer to add the quality characteristic "energy efficiency" up to the point where its marginal cost equals its value in energy saving to the consumer. There will be no change in the service price of the new-model refrigerator compared to that of an old model in the new energy price regime, since the reduction in the annual value of energy consumption will offset the increase in the annual depreciation and interest cost of the higher quality refrigerator. In exactly the same way, my own procedure would find that there had been an increase in net revenue measured at constant fuel prices that was proportional to the higher unit price of the equipment, and consequently no quality adjustment would be called for.

Now consider a "nonproportional" innovation that cut annual expenditures on energy by $20, while increasing the annual capital cost of a refrigerator by only $10. Triplett's service price of refrigerators would register a decline, as would my price index for refrigerators based on a finding that net revenue had increased by more than equipment cost.[1] Either measure of price would be adequate for a study of the demand for refrigerators in a period of constant energy prices and would be far preferable to an index that failed to register any decline in price. In the case of commercial aircraft, the subject of the empirical study in my paper, a demand study for the 1950s and 1960s (a period of roughly constant fuel prices), would be highly misleading if it used the official BEA price index.

Despite the equivalence of the service price concept and my quality adjusted price index in this example, for general purposes the two concepts are not equivalent in periods like the 1970s when fuel prices have changed. The second part of my argument is that, while the service price measure must be used in demand studies to reflect the adverse impact of rising fuel prices on the demand for aircraft, the national income and product accounts must be based on a quality adjusted price index that holds the costs of fuel and maintenance labor constant. Since our basic measures of net national product and aggregate productivity include net investment as a major component, price indexes used for deflation in the national accounts should incorporate a quality adjustment procedure that decomposes changes in the service prices of durable goods into a portion "caused" by the manufacturer and a remaining portion (including changing fuel prices) that occurs after the equipment is acquired by the user. If we are only interested in an input index like the CPI, a comprehensive service price concept would be sufficient. But for the measurement of net investment in the national accounts, changes in service prices must be split between manufacturers and users.

Why is it important to measure changes in energy efficiency achieved by the manufacturer? Consider a hypothetical nonproportional innovation that doubled aircraft speed with no increase in aircraft price. This would represent a decline in the price of aircraft seat-miles per unit of time, an increase in the real capital represented by the new-model aircraft, and thus an increase in net investment and net national product. Let us imagine instead that the same research expenditures in the aircraft industry were invested in lower fuel usage rather than in faster speed, and let us assume that a hypothetical energy-saving innovation yielded precisely the same increase in airline net revenue as a doubling of aircraft speed, with no increase in aircraft price. The service price of aircraft (including capital cost and fuel expense) measured per seat-mile would fall by the same amount in either case, and a price index for aircraft services that held constant the price of fuel would fall in proportion. My justification for energy-efficiency adjustments is that changes in service price that occur with fixed input prices should be credited to the manufacturer of the equipment, reflecting the observation that major nonproportional shifts in both performance and energy efficiency tend to be "embodied" in capital goods by their manufacturers rather than achieved by their users. When fuel prices are held constant, a service price criterion and my net revenue criterion lead to the same quality adjustment, because they are two different methods of measuring the same thing.

My quality adjustment procedure is essential not only to capture the higher level of net investment and the higher level of aggregate productivity resulting from energy-saving innovations, but also to allocate correctly the credit for the innovations to the industry achieving them—the airframe and aircraft engine industries in my example rather than the airline industry. The importance of a correct allocation is obvious for those who are attempting to trace the current U.S. productivity slowdown to changes in capital and R&D input in particular industries (Griliches 1980). Such studies will be hopeless failures if they credit the achievements of the research-intensive aircraft industry to the airline industry, which does no research at all!

Note

1. Consider the following division of annual operating revenue: (*a*) annual labor cost, (*b*) annual fuel cost, (*c*) annual capital cost (interest plus depreciation), (*d*) annual profit. Triplett's service price includes *b* plus *c*. A nonproportional improvement in energy efficiency by definition reduces *b* more than it raises *c*, thus reducing the service price. My "net revenue" is *c* plus *d*. A nonproportional improvement in energy efficiency by my definition raises net revenue (*c* plus *d*) by more than capital cost (*c*) when calculated at fixed prices of output, labor, and fuel. Thus both criteria give the same answer; the reduction in service price parallels the decline in the equipment price index that results from my method.

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