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PRODUCT INNOVATIONS, PRICE INDICES AND THE (MIS)MEASUREMENT OF ECONOMIC PERFORMANCE

by

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ABSTRACT

The purpose of this paper is to address the problem of 'product innovations' (i.e. new goods, increased variety, and quality change) in the construction of price indices and, by extension, in the measurement of economic growth. The premise is that a great deal of technological progress takes indeed the form of product innovations, but conventional economic statistics fail by and large to reflect them. The approach suggested here consists of two stages: first, the benefits from product innovations are estimated with the aid of discrete-choice models, and second, those benefits are used to construct 'real' (or 'quality adjusted') price indices. Following a discussion of the merits of such approach vis a vis the use of hedonic price indices, I apply it to the study of a specific innovation, namely CT (Computed Tomography) Scanners. The main finding is that the rate of **decline** in the quality-adjusted price of CT scanners was a staggering 55% per year (on average) over the first decade following the invention of CT. By contrast, an hedonic-based 'real' index captures just a small fraction of the decline, and worse still, a simple (unadjusted) price index shows a substantial price **increase** over the same period. Thus, conventional indices might be missing indeed a great deal of the welfare consequences of technical advance, particularly during the initial stages of the product cycle of new products. It remains to be seen, though, how much of the paradox of explosive technical change on the one hand, and 'low' measured growth rates on the other could be accounted for by this sort of discrepancies.

1. Introduction

The purpose of this paper is to address the problem of 'product innovations' (i.e. the introduction of new goods, increased variety, and changing qualities of existing brands) in the construction of price indices and, by extension, in the measurement of economic growth. The underlying premise is that a great deal of technological progress takes indeed the form of product innovations, but conventional economic statistics (e.g. 'real product', productivity growth, and the like) fail to reflect them, quite likely by a long shot. Key to the problem is the fact that conventional index-numbers methods cannot possible capture quality change, and that, as argued extensively below, hedonic price indices may offer some paliative but by no means a full cure. As it stands now, then, there is no proven way of incorporating product innovations into measures of economic performance, and hence no way of assessing the possible discrepancies that might exist on that account between 'real' and conventionally measured aggregate product and growth.

Acting on the belief that the 'goodness' of a deflator is to be judged according to its ability to capture changes in consumers' welfare, I sketch first an econometric approach for measuring **directly** the benefits from product innovations, which I have laid out in detail in previous work (Trajtenberg, 1989a,b). The proposed method draws primarily from discrete choice models and from the 'characteristics approach' to demand theory, leading to estimates of the preferences for the attributes of products, and from there to **value** measures of quality changes. The novelty here resides in using those measures in order to construct 'real' (or 'quality adjusted') price indices. That is, having obtained money measures of the gains (in terms of consumer surplus) from product innovations, I show a way to express those gains as changes in 'real' prices. Following a discussion of the merits of such approach vis a vis the use of hedonic price indices, I apply it to the study of a specific innovation, namely CT (Computed Tomography) Scanners. The main finding is that the rate of **decline** in the quality-adjusted price of CT scanners was staggering (averaging 55% per year over 9 years), particulary during the first few years following the introduction of the innovation. By contrast, an hedonic-based 'real' index captures just a small fraction of the decline, not to speak of the unadjusted price index, which shows a substantial price **increase** over the same period.

Thus, conventional indices might be missing indeed a great deal of the welfare consequences of technical advance, particularly during the initial stages of the product cycle of new products.[1] Rather than merely stating once again the suspicion that we might be therefore mismeasuring growth, the approach taken here is a constructive one and offers a pragmatic way of dealing with the problem. True, its application requires both the gathering of more extensive and detailed data (primarily on the quality dimensions of products and on market shares), and the use of more advanced econometric techniques (e.g. discrete choice models). However, it is my belief that both tasks are well within the realm of the feasible, and that it is increasingly important to do that if the presumed link between aggregate economic measures

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[1] This is above and beyond the problem of the long delays in incorporating new goods in the computations of say, the CPI. That is, even if new goods were incorporated right away in existing price indices, the problem of mismeasurement will remain.

(such as GNP) and 'economic well-being' is to be preserved.

Finally, a comment about accounting for the infamous 'productivity slowdown', or addressing the apparent paradox of explosive technical change on the one hand, and 'low' conventionally measured growth rates on the other. As has been repeatedly pointed out (see e.g. Baily and Gordon, 1988), it is not enough to uncover (yet another) source of mismeasurement: one has to show, first, that we are measuring things worse now than before, and second, that the problem is widespread and substantial enough to make a real dent in the growth statistics. Unfortunately, on both accounts I can just offer at this stage my intuitive sense of what is going on, and no more. First, it is often claimed that technical change has been taking increasingly the form of product innovations (as defined above), rather than process innovations (i.e. cost reductions in the production of given goods), particulary so since the advent of electronics. If that were the case (and I tend to believe so), then conventional price indices would indeed be less and less capable of capturing technical advance, and the gap between 'real' and perceived growth would be increasing over time. Clearly, though, one would have to offer convincing quantitative evidence of this alleged change in the 'mix' of technical advance in order to make the argument stick.[2] Second, the evidence presented below regarding the extent of mismeasurement refers, as said, just to one case study. Again, I believe that the qualitative phenomena uncovered in that study (particulary the fact that the largest gains from innovation occur at the very beginning, when the mismeasurement problem is most acute), may hold for great

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[2] See Scherer (1984) for some tentative evidence pointing in that direction.

many high-tech products. However, many more studies of this sort will be needed if that belief is ever to be substantiated.

2. The Assessment of Product Innovations

In view of the fact that the 'output' of innovative activities does not present itself in countable units of any sort, innovations can only be quantified directly in value terms, i.e. in terms of their impact upon social welfare. Thus, the question "how much innovation has taken place" in a certain field over a certain period of time, can only be interpreted as asking "how much additional consumer and producer surplus was generated by technical advance in that field and time."[3] If the innovation takes the form of cost reductions in the production of given products, then the assessment of its value is conceptually straightforward, involving the displacement of cost functions along a fixed demand schedule (see e.g. Griliches, 1958). On the other hand, if the innovation consists of the introduction of new products or changes in the quality of existing ones, then its value to consumers cannot be represented simply as a cost saving but requires instead a more elaborate framework.

The methodology for the assessment of **product** innovations put forward in Trajtenberg (1989a) draws primarily from the 'characteristics approach' to demand theory and from the econometrics of discrete choice models.[4] The basic

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[3]Alternative measures such as patent counts, counts of 'important innovations', rates of change of attributes, etc. could play at best the role of proxies, and their accuracy as such can be judged only by relating them to the value measures themselves (see e.g. Trajtenberg, 1987).

[4]The methodology is discussed in full in Trajtenberg (1989b) - here I

idea is as follows: consider a technologically dynamic product class as it evolves over time, and assume that the different brands in it can be described well in terms of a small number of attributes and price. Product innovation can then be thought of in terms of changes over time in the set of available products, both in the sense that new brands appear, and that there are improvements in the qualities of existing products. Applying discrete choice models to data on the distribution of sales per brand, and on their attributes and prices, one can estimate the parameters of the demand functions and, under some restrictions, of the underlying utility function. The social value of the innovations occuring between two periods can then be calculated as the benefits of having the latest choice set rather than the previous one, in terms of the ensuing increments in consumer and producer surplus.

To fix ideas, define $s_i \equiv (z_i, p_i)$, where p_i stands for the price and z_i for the vector of characteristics of product (brand) i in a given product class. The choice set from which the consumer selects the most preferred brand in period t is thus $S_t = (s_{1t}, s_{2t}, \ldots, s_{nt})$. In this setting product innovation is taken to mean simply that changes occur over time in the vectors z_i and in n_t, and hence that the choice set changes from S_{t-1} to S_t. Given a 'social surplus' function $W(S)$,[5] and assuming that the changes in S are discrete, the magnitude of innovations occuring from t-1 to t will be measured by,

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present just a brief sketch of its main elements.

[5]W(S) is meant to comprise both consumer and producer surplus. However, since profit is a well-defined magnitude whose measurement does not pose special conceptual problems in the present context, ΔW will be associated with gains from innovations in terms of consumer surplus only.

(1) $$\Delta W = W(S_t) - W(S_{t-1})$$

The main problem, then, is to find a suitable specification for the function $W(S_t)$, and be able to retrive its parameters from observable data. In principle, this is to be done by integrating over the underlying demand function, whose features would depend, inter alia, on whether the choice set is continuous or discrete. In the context of technologically-progressive products it seems appropriate to characterize those sets as discrete: R&D constitutes a fixed cost, and hence innovative sectors typically exhibit in equilibrium a finite and not-too-large number of differentiated products.[6] Discreteness is assumed also in the sense that consumers purchase a single unit of a single product, thus making the choice problem exclusively qualitative (the analysis can be easily extended to accomodate cases of discrete/continuous choice as well). Those assumptions allow one to resort to discrete choice models, and make use of the associated welfare analysis (see McFadden, 1981).

The basic hypothesis underlying discrete choice is that consumers maximize a random utility function, $U_i = U(z_i, m; h) + \epsilon_i$, subject to $s_i \in S$, and $p_i + m = y$, where m denotes a composite 'outside' good, h a vector of observable attributes of the individual, and ϵ_i an i.i.d. random disturbance. Assuming that ϵ_i conforms to the type I extreme-value (or

[6] Rosen (1974) analysed the continuos case and laid out the basis for the econometric estimation of such a system. However, the implementation of Rosen's approach poses serious difficulties, as discussed in detail by Epple (1987).

Weibull) distribution, the mazimization of U_i leads to probabilistic demand functions of the form,

$$(2) \qquad \pi_i = \exp V_i \Big/ \sum_j^n \exp V_j \,, \qquad i = 1,\ldots,n$$

where V_i is the deterministic component of the conditional indirect utility funtion, and π_i are **fractional** demands (thus, $\Sigma\, \pi_i = 1$): this is the well known conditional multinomial logit model (MNL). It is easy to prove that the n equations in (2) constitute a well-behaved demand system, and hence the notion of consumer surplus applies to it as well, and can be computed by integration. To make the problem more tractable income effects are assumed away, i.e. the utility function is specialized to be additive separable in the group products (those in S) and in the outside good m, rendering $V_i = \alpha(y - p_i) + \phi(z_i,h)$, where α stands for the (constant) marginal utility of income. Substituting in (2),

$$(3) \qquad \pi_i = \exp\,[-\,\alpha p_i + \phi(z_i;h)] \Big/ \sum_{j=1}^{n} \exp\,[-\,\alpha p_j + \phi(z_j;h)]$$

The identity of hicksian and marshallian demand functions in (3) allows one to obtain the surplus function W(S,h) simply by integrating under these demand functions, the integral being path independent. Ignoring the constant of integration, the result is,[7]

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[7]Note that, in dividing by α, the function W(.) is being normalized so as to express it in money terms. Notice also that $-\partial W/\partial p_i = \pi_i$, and hence (4)

(4) $$W(S,h) = \ell n \left[\sum_{i=1}^{n} \exp(-\alpha p_i + \phi(z_i;h))\right] / \alpha$$

This surplus function is then the key element in assessing the value of product innovations: after estimating the choice probabilities in (3), one can retrieve the parameters of (4), and compute the benefits from innovations occuring between any two adjacent years, as in (1). One of the problems that may arise in estimating (3) is that prices and characteristics are typically highly correlated, and the ensuing multicollinearity makes it very difficult to obtain reliable estimates of the parameters of (4). The solution put forward in Trajtenberg (1989a) involves the use of residuals from estimated hedonic price funtions in a multi-equation context (see the Appendix). Thus, hedonic price functions may still have an important role to play in assessing product innovations, even though they might not be sufficient by themselves as indicators of quality changes.

3. The Construction of Quality-Adjusted Price Indices on the Basis of ΔW

Suppose then that we have estimated the multinomial logit model as in (3) and computed the yearly gains ΔW_t from (4) and (1); the question now is how to construct on the basis of those ΔW's a 'real' price index that would faithfully reflect the innovations that had occured. The procedure to be put forward here involves relying on the expenditure function dual to (4), and using it to compute the hypothetical price change that would have resulted in

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is indeed the correct solution.

the same welfare effect (measured by ΔW) as the innovations that actually took place. In that sense the proposed index belongs to the class of 'cost-of-living' - or Konüs - indices (see Diewert, 1987).

Consider the function,

$$V = \frac{y}{\bar{P}} + W(S) = \frac{y}{\bar{P}} + \ell n \left[\sum_{i=1}^{n} \exp(-\alpha p_i + \phi(z_i)\right]/\alpha$$

where $\bar{P}$ is the price of all goods other than those in S (i.e. the price of the numeraire, implicitly assumed before to be unity), and the prices p_i appearing in $W(S)$ are now 'real', i.e. $p_i = \tilde{p}_i/\bar{P}$, where $\tilde{p}_i$ are nominal. Note that V is homogenous of degree zero in prices and income, and convex in prices. Thus, and as shown in McFadden (1981), (5) is in fact an indirect utility function, and is therefore invertible to a (concave) expenditure function, $e(S, V^o) = \bar{P}\cdot[V^o - W(S)]$. Given that $\bar{P}$ will not play a role in the forthcoming analysis, we can ignore it and write,

(5) $$e(V^o, p, Z) = V^o - \ell n \left[\Sigma \exp(V_i) \right]/\alpha$$

where p stands for the **vector** of prices of all brands in S, and Z for the matrix of their attributes. Assume now that innovations occur from period $t-1$ to t, taking the form of improvements in the attributes of - some of - the products in the choice set (their prices may change as well). Using (1), (4) and (5), the welfare gains from those innovations would be measured by,

$$\Delta W_t = \ell n\ [\Sigma \exp(V_{it})\ ]/\alpha - \ell n\ [\ \Sigma \exp(V_{it-1})\ ]/\alpha \quad \Rightarrow$$

$$\Delta W_t = e(V^o,\ p_{t-1},\ Z_{t-1}) - e(V^o,\ p_t,\ Z_t) \tag{6}$$

Thus, ΔW as expressed in (6) measures the analog in the present context of a **compensating variation,** i.e. it answers the question "how much income could be taken away from the consumer so as to leave him indifferent between facing the old choice set, and the new (improved) one but with the lesser income?" However, since $e(\cdot)$ is linear additive in V (recall that income effects were assumed away), then the reference utility level (or the income level in the dual) does not matter, and hence the compensating and equivalent variations are one and the same. Thus, we can ommit V^o from (6) and write:

$$\Delta W_t = e(p_{t-1},\ Z_{t-1}) - e(p_t,\ Z_t) \tag{6'}$$

Once estimates of ΔW_t have been obtained using the method outlined in section 2, one can construct two different price indices that would reflect the quality changes embedded in S_t vis a vis S_{t-1}. The first requires that we solve for δ_t out of,

$$\Delta W_t = e[p_{t-1},\ Z_{t-1}] - e[\ (1-\delta_t)\cdot p_{t-1},\ Z_{t-1}] \tag{7}$$

(to insist, ΔW_t in (7) is a known magnitude, and so are the parameters of the expenditure function). That is, δ_t is the hypothetical average price reduction that would have had the same welfare consequences as the innovations that actually took place. In other words, consumers would had been equally well off if they had been offered the **old** set of products at prices lower by a factor of δ_t, as they actually are by virtue of having the **new** set that incorporates the better qualities (i.e. they would be indifferent between $[(1-\delta_t)\cdot p_{t-1}, Z_{t-1}]$ and $[p_t, Z_t]$). From a computational viewpoint, the values of δ_t can be obtained from (7) with methods of iterative search.[8] However, if one is willing to use a somewhat more restrictive notion of 'average price change', then δ_t can be computed in a much simpler way. This is done as follows: the price of each brand at time t can always be written as $p_{it} = \bar{p}_t + \Delta p_{it}$, where $\bar{p}_t$ is the average across brands. Now, suppose that the changes in prices from period t-1 to t take the from,

$$p_{it} = (1 - \delta_t)\, \bar{p}_{t-1} + \Delta p_{it-1}$$

that is, the distribution of prices moves leftwards by a factor of $(1 - \delta_t)$, but the variance remains the same. It is easy to show that in such a case (7) simplifies to,[9]

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[8]Note from (6)' and (7) that this is the same as solving for δ_t out of $e[(1-\delta_t)\cdot p_{t-1}, Z_{t-1}] = e[p_t, Z_t]$.

[9]Recall that $W = \ell n[\Sigma_i \exp(\phi_{it} - \alpha p_{it})]/\alpha$, where $\phi_{it} = \phi(z_{it})$. Given $p_{it} = \bar{p}_t + \Delta p_{it}$, $W = \ell n[\Sigma_i \exp(\phi_{it} - \alpha\bar{p}_t - \alpha\Delta p_{it})]/\alpha = \ell n\{[\Sigma_i \exp(\phi_{it} - \alpha\Delta p_{it})] \exp(-\alpha\bar{p}_t)\}/\alpha = -\bar{p}_t + \ell n[\Sigma_i \exp(\phi_{it} - \alpha\Delta p_{it})]/\alpha$. Therefore, given $\bar{p}_t = (1-\delta_t)\bar{p}_{t-1}$, (7) reduces to $\Delta W_t = \bar{p}_{t-1} - (1 - \delta_t)\bar{p}_{t-1} = \delta_t\bar{p}_{t-1}$.

(8) $$\Delta W_t = \delta_t \bar{p}_{t-1}$$

and hence δ_t obtains immediatly as the ratio $\Delta W_t/\bar{p}_{t-1}$. To reiterate its meaning, this ratio stands for the percentage average price reduction that would be equivalent, from a welfare viewpoint, to the innovations valued ΔW_t. This is a very convenient result for computational purposes, and it may help clarify the meaning of the measure ΔW_t itself (e.g. it may be easier to visualize ΔW_t as a displacement along the price dimension). Having arrived at the series $\{\delta_t\}$, a quality adjusted price index can then be computed simply as $I^1_t / I^1_{t-1} = (1 - \delta_t)$, with $I^1_0 = 100$ (the superscript is meant to distinguish between the two alternative indices)

The second price index obtains by solving for φ_t from,

(9) $$\Delta W_t = e[\ (1+\varphi_t)\cdot p_t,\ Z_t] - e[\ p_t,\ Z_t]$$

That is, if prices of the improved products had been $(1+\varphi_t)$ times higher than actual prices, then the implied price reduction of $\delta'_t = \varphi_t/(1+\varphi_t)$ % would be equivalent - from the point of view of its welfare effects - to the quality improvements that took place. Thus, $(1+\varphi_t)\cdot\bar{p}_t$ can be interpreted as the reservation price for the innovations embedded in S_t: if the products in that set were offered at an average price of $(1+\varphi_t)\cdot\bar{p}_t + \epsilon$ (for any small $\epsilon > 0$), the consumer would prefer to have the older set instead. Assuming again that the price change consists just of a displacement in the mean price, φ_t would obtain simply from,

(10) $$(1+\varphi_t) = (\Delta W_t + \bar{p}_t) / \bar{p}_t \Rightarrow \varphi_t = \Delta W_t / \bar{p}_t ,$$

implying a percentage price reduction of,

(11) $$\delta'_t \equiv \varphi_t / (1+\varphi_t) = \Delta W_t / (\Delta W_t + \bar{p}_t)$$

The associated price index would be $I^2_t / I^2_{t-1} = 1/(1+\varphi_t) = (1 - \delta'_t)$.

Comparing the two indices, it can be shown that $\delta'_t \leq \delta_t$, i.e. the first index will always show a larger 'quality-ajusted' price reduction. This is easily seen in the case where $\bar{p}_t = \bar{p}_{t-1} = \bar{p}$:

$$\delta_t = \frac{\Delta W_t}{\bar{p}} > \frac{\Delta W_t}{\Delta W_t + \bar{p}} = \delta'_t$$

That is, ΔW_t (to be interpreted here as a notional average price discount equivalent to the quality improvements), would certainly represent a higher percentage of the base price $\bar{p}$, than of the - necessarily higher - 'reservation price' $(\Delta W_t + \bar{p})$.[10] In general, though, $\bar{p}_t \neq \bar{p}_{t-1}$, but the above inequality will still hold. Denoting $\bar{p}_t = (1+\lambda_t)\cdot\bar{p}_{t-1}$, it is easy to show that $\delta' = \frac{\delta_t}{1 + \lambda_t + \delta_t}$, and hence that $\delta'_t < \delta_t$;[11] notice also that the

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[10]This is the same sort of discrepancy as the one that may arise when computing the elasticity of say, a demand function, along a segment (i.e. for a discrete price change), rather than at a point.

[11]This is so provided that, if $\lambda_t < 0$ (i.e. if there is an average price **reduction**), then $|\lambda_t| \leq \delta_t$. But that is always the case (unless there is a quality deterioration): if the qualities of products don't change from t-1

difference between the two indices grows with λ_t.

Clearly, the two indices are equally legitimate and have equally well defined welfare interpretations. There is, however, a technical difference between them that makes the second index the only feasible one when innovations are 'drastic' i.e. when the ΔW's are very large (relative to prices). Note that there is no reason whatsoever for ΔW_t to be smaller than $\bar{p}_{t-1}$ (i.e. there is no reason for the **value** of innovations to be bounded by the average price of the products embedding those innovations), and hence it may happen that $\Delta W_t > \bar{p}_{t-1}$ (i.e. that $\delta_t > 1$). That would mean simply that, even if the products that existed in period t-1 were to be sold at zero price, consumers would still prefer to have instead the more advanced products and pay their full price. In other words, in order for consumers to be indifferent between facing the period t choice set and that of period t-1, they would have to be offered the t-1 products for free, plus a 'bribe' (or 'negative price') of $(\Delta W_t - \bar{p}_{t-1})$ dollars. However, since negative prices are not allowed one could not use in such a case I_t^1, since $\delta_t > 1$ would imply a negative value for the index. On the other hand, if ΔW_t is larger than $\bar{p}_t$ and hence $\varphi_t > 1$, the second index is still well defined: the hypothetical reservation prices that would make the consumer indifferent between the improved (but more expensive) products and the older set can be as high as necessary.

Thus, if innovations in a given field are at times very substantial there is no choice but to use the second index only. On the other hand, if a field

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to t but $\bar{p}_t = (1-\lambda)\bar{p}_{t-1}$, then $\Delta W_t = \lambda\bar{p}_{t-1}$, and hence $\delta_t = \lambda_t$. If at the same time qualities improve, then $\delta_t > \lambda_t$.

consistently displays just incremental innovations it may be worth considering some sort of average between the two indices, and/or using the average of the mean price in the two periods to compute either index. Finally, it is worth noting that those indices can accomodate well cases of 'negative' innovations, resulting in negative values of ΔW_t. That would be the case, for example, if there is no change in the qualities of products, but prices **rise** by λ%: it is easy to see that in such a case $\delta'_t = \delta_t = -\lambda$, i.e. both indices would faithfully and equally reflect the price hike.

4. ΔW-based Indices versus Hedonic Prices

Having thus put forward price indices based on the measures ΔW, it is important to step back and ask whether one really needs the - rather complicated - method outlined above in order to obtain reasonably good deflators for rapidly changing goods: could it not be that indices based on hedonic price regressions would do the job just as well?[12] It is important to note that this question is in fact equivalent to asking whether or not there is a meaningful distinction between process and product innovations: as I shall argue below, the use of hedonic price indices (in lieu of ΔW-based indices) is justified only when 'quality' is merely a redefinition of quantity, and hence 'product innovation' is just process innovation in disguise.

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[12]The hedonic method is certainly much simpler, its data requirements are more modest, and it has the extra advantage of having been already accepted, albeit partially, by the US Bureau of Labor Statistics (i.e. in computing a price index for computers). Thus, if both methods were roughly equivalent, surely one would not hesitate in siding with the hedonic approach.

4.1 Quality-Adjusted Price Indices in The 'Repackaging' Case

The answer to the question just posed can essentially be found in Fisher and Shell (1972) classic work on the theory of price indices (even though the question was not quite put in those terms there): hedonic-based price indices (or a price/performance ratio if 'quality' is unidimensional) would suffice to account for quality change only in the 'repackaging' case. If the choice set consists of one good only (say, good 1), and 'quality' can be fully accounted for with one parameter θ, 'repackaging' implies that the corresponding argument in the utility function is just θx_1. That is, θ is sort of the amount of services provided by the good, and hence 'quality change' (meaning $\theta_t > \theta_{t-1}$) amounts essentially to a redefinition of units. In such a case one can define a 'price-performance' ratio p_1/θ such that, for any θ,

$$e(V^o, p_1, p_2, \ldots, p_n; \theta) = e(V^o, p_1/\theta, p_2, \ldots, p_n) \tag{12}$$

and the implied 'quality adjusted' price index would simply be (p_{1t}/θ_t) / (p_{1t-1}/θ_{t-1}). Thus, if θ were easily observable (as when it is indeed just a matter of redefining units), accounting for 'quality change' would be a very simple matter. Notice, importantly, that in such a case the distinction between process and product innovations all but vanishes (as does the quality-quantity dichotomy): defining the relevant price as p_1/θ, rather than just p_1, it is clear that technical change that brings about a reduction in costs leading in turn to a decrease in the unadjusted price p_1 (i.e. a **process** innovation) is exactly equivalent to a 'product' innovation that results in the enhancement of θ.

When the choice set consists of $n > 1$ brands, 'repackaging' implies that the corresponding branch of the utility function takes the form $U(\Sigma_i^n \theta_i x_i)$. Clearly, if $U(\cdot)$ is common to all consumers, then in order for more than one brand to be purchased in a cross-section it must be that $p_i/p_j = \theta_i/\theta_j$. Denoting by $\tilde{p}_o$ the quality-adjusted price of the reference variety, one can always write $p_i = \tilde{p}_o \theta_i$. Furthermore, if θ_i is not one-dimensional but depends upon a vector of attributes $\bar{z}_i$, then (see for example Deaton and Muellbauer, 1980),

$$\log p_i = \log \tilde{p}_o + \log \theta(\bar{z}_i) \tag{13}$$

which is one of the forms that estimated hedonic price functions commonly take. In a two-year panel, for example, the term $\log \tilde{p}_o$ would obtain as the coefficient of a time dummy variable, and can be taken as a sufficient price index in the sense of (12) above (i.e. $\tilde{p}_t$ would be the equivalent in this context of the price-performance ratio p_t/θ_t).[13] To insist, the point is that the hedonic price function by itself just allows to account for more than one attribute in computing price indices, but such indices can serve as sufficient indicators of 'quality' change only in the highly restrictive context of the repackaging case.

4.2 Product Innovations, Repackaging, and the Nature of Characteristics

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[13] Even this simple case is subject to several qualifications. In particular, if the budget constraint in attributes space is non-linear (as it is most likely to be), then the estimation of (13) involves what can be construed as errors of aggregation.

In order to get a better understanding of what lies behind the repackaging case (and hence be able perhaps to assess its empirical relevance), it is worth examining carefully the notion of quality implied by it, and the sort of attributes of products that would support such notion. Following the discussion on the nature of products' attributes in Trajtenberg (1979), I distinguish between concatenable and non-concatenable characteristics,[14] the former being formally defined as

$$z_{ij} = f^j(x_i), \qquad \frac{\partial z_{ij}}{\partial x_i} \neq 0 \qquad \text{for} \quad x_i \geq 0$$

and the latter as

$$z_{ij} = g^j(\omega_i), \qquad \frac{\partial z_{ij}}{\partial x_i} = 0 \qquad \text{for all} \quad x_i \geq \omega_i$$

where ω_i denotes the 'natural unit' of product i and x_i its quantity. Typical examples of concatenable characteristics are proteins in food products, or carrying capacity of vehicles, i.e. the amount of the characteristics available to the consumer is a monotonic function, usually linear, of the quantity of the product(s) consumed. Non-concatenable characteristics, on the other hand, are much closer to the intuitive notion of quality, that is, they are properties inherent to the product as such, and do

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[14]This terminology, borrowed from the theory of measurement (see Krantz **et al** ,1971), was meant to focus attention on the physical properties that underlie the different kinds of measurement, and their implications for economic behavior. Concatenation is an operation by which objects are connected with respect to some common attribute, allowing for 'extensive measurement' (e.g. the placing of rods edge to edge for the measurement of length).

not vary with its quantity (e.g. speed of vehicles, aperture of photographic cameras, etc.). Therefore, different amounts of characteristics can be obtained only by switching products, and not by adjusting the quantities consumed.

Similar distinctions have been made in the literature,[15] and the various 'characteristics models' available can be categorized, at least a posteriori, in terms of it. Thus, for example, the original model of Lancaster (1971) clearly corresponds to the case where products have **only** concatenable attributes. On the other hand, Rosen (1974), and Lancaster's second model (1979), among others, have addressed the non-concatenability case. However, the relevance of this sort of distinction for the conceptualization of innovations has not been well-established, let alone its implications for price indices.

It is easy to see that when the product in question has just one relevant attribute, concatenability entails the simple repackaging case, i.e. the utility branch is just $U(z)$, $z = b x_1$, where b is the per-unit amount of the characteristic, obviously identical to θ in (12) above. Noting that concatenability implies that the amount of characteristics can be added up both over units of one product and over units of different products, the case of product variety obtains in a straightforward manner (i.e. $z = \Sigma b_i x_i \equiv \Sigma \theta_i x_i$). When the θ_i's (and hence utility) depend upon more than one characteristic, then concatenability and repackaging are equivalent only under

[15] Although mostly in an implicit and informal manner (when explicit, the distiction has been refered to in a variety of ways, e.g. combinable vs. non-combinable, additive vs. non-additive, etc.). Moreover, the different types of attributes are just assumed, not explained in terms of more primitive elements.

more restrictive assumptions regarding the form of the utility function (see Muellbauer, 1974). However, concatenability of the composite quality indicator $\theta(\bar{z}_i)$ itself is still a sufficient condition for repackaging.

Thus, in order for there to be a distinct and meaningful notion of quality and of product innovation, **some** of the characteristics of the product (i.e. at least one) have to be non-concatenable. Otherwise the choice set would be homogeneous of degree zero in prices and characteristics, implying that consumers would necessarily be indifferent between price reductions and increases in the per-unit quantity of all characteristics (regardless of their preferences).[16] In other words, the point is that the notion of product innovation is inextricably related to, and presupposes the existence of a distinct quality dimension (that is, distinct from a mere redefinition of units), and since non-concatenability is essential for the latter, it is by extension a **sine qua non** for the former.

The obvious question is, what do we gain by stating the problem in terms of concatenability rather than repackaging? The intention is to make the distinction empirically applicable, by focusing on observable properties of attributes. In other words, when considering if technical advances in a certain field can be assessed as if they consisted just of cost reductions, or whether they are to be treated instead as product innovations (hence

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[16] To illustrate the point, consider the case where there is a change in product $s_i = (z_i, p_i)$ such that $s_i' = (\lambda z_i, \lambda p_i)$, $\lambda > 1$. If all characteristics were concatenable then the move from s_i to s_i' could not be regarded as an innovation at all, and would not have any welfare consequence, since $V(s_i, y) = V(s_i', y)$. On the other hand, if some of the attributes were non-concatenable then the same change will certainly qualify as an innovation, and would probably have a sizeable welfare impact.

necessitating ΔW-based price indices), one should proceed as follows: first, find out what the relevant attributes of the goods in question are. Second, examine whether those attributes exhibit the concatenability property, i.e. check whether or not it is possible to 'join' (if not physically at least conceptually) two or more units of the good with respect to each of the attributes, so that the summing operation $z_i = \Sigma b_{ij}x_j$ would be well-defined and meaningful utility-wise. If the answer is positive, then one is on sound grounds estimating quality-adjusted price indices on the basis of hedonic price functions, and using them as deflators for e.g. growth accounting. Otherwise product innovation is the name of the game, and the approach outlined in previous sections is called for. Finally, note by contrast that the notion of repackaging in itself does not lead to a well-defined test having empirical relevance (at least it is not transparent how one would go about testing for it).

Put in that way, it is quite clear that few cases (i.e. few product classes in the economy) would pass the strict concatenability test. Thus, and more realistically, rules could be devised by which the choice of method for the computation of price indices would depend upon the type which **most** of the attributes correspond to. Still, it seems that a large number of products would fail even a lenier test of that kind, and hence that we may be missing a great deal by forcing product innovations into the narrow mold of price-performance ratios or hedonic price indices (or simply ignoring them). Thus, the claim made to the effect that conventional price indices may actually be doing quite well in accounting for innovation (see for example Triplett 1975), needs to be given a good hard look once again.

4.3 Assessing the Performance of Hedonic-Based Price Indices

One of the intended uses of the price index based on the measures ΔW_t's, is for it to serve as a test criterion for other indices and, in particular, for hedonic-based indices. That is taken up empirically in the next section, where both indices are computed and compared for the case of CT scanners. However, in order to have a better sense for what those comparisons may entail, it is worth examining in a heuristic manner how hedonic price indices are likely to perform in various stylized situations.

Quite clearly, if a price index is to account faithfully for quality change, it should measure the 'distance' (in money metric) between the attainable utility level before and after the innovation. Consider the case where innovations occur so that there is a downward shift in the hedonic function, as shown in Figure 1.a. In the simplest possible situation (abstracting from discreteness, aggregation problems, and income effects), the distance between the indifference curves labeled W^o and W' would be a good approximation to the monetized welfare gains associated with the innovations that induced the displacement in the hedonic function. Thus, the coefficient of a time dummy in a hedonic regression pooling adjacent years will accurately measure those gains, and the resulting quality-adjusted price index could thus be taken as a faithful indicator of the changes occured.

In order to illustrate this equivalence, assume that there is only one attribute, z, and that innovation consists of augmenting the quantity of that attribute in all brands by the same absolute magnitude, Δz (if prices remain unchange, as it is assumed, that will result in a parallel displacement of p(z) as in Figure 1.a). Evaluating this change with the measure ΔW of equation (6), and further assuming that $V(\cdot)$ is linear in z,

$$\Delta W = \ln \{ \Sigma \exp[-\alpha p_i + \beta (z_i + \Delta z)]\}/\alpha - \ln [\Sigma \exp(-\alpha p_i + \beta z_i)]/\alpha =$$
$$\beta \Delta z/\alpha$$

Now, if the hedonic function is also linear, i.e. $p_i = \bar{p} + \gamma z_i$, then it is easy to see that the implied price index will change by $\Delta\bar{p} = \gamma \Delta z$.[17] Thus, $\Delta\bar{p}$ and ΔW will be proportional to each other and, under a suitable normalization, they will be identical. This is of course a highly simplified case, but the gist of the argument applies in more complex situations as well.

By contrast, consider now Figure 1.b: innovation in this case consists of the filling-up of the spectrum of products, e.g. in the base period only brands 1, 2 and 3 exist, but in the second period products such as 4 and 5 are added to the choice set. As the figure suggests, in this case there will be no change whatsoever in the hedonic price function, and hence a price index based on it will altogether fail to register the occurance of the innovations. On the other hand, a measure such as ΔW will certainly be positive, and could in fact be quite large. Figure 1.c illustrates a similar situation, except that innovation takes there the form of extending the range of available products, i.e. higher quality brands are introduced, priced (approximately) in accordance to the base hedonic function. Again, this type of innovations will

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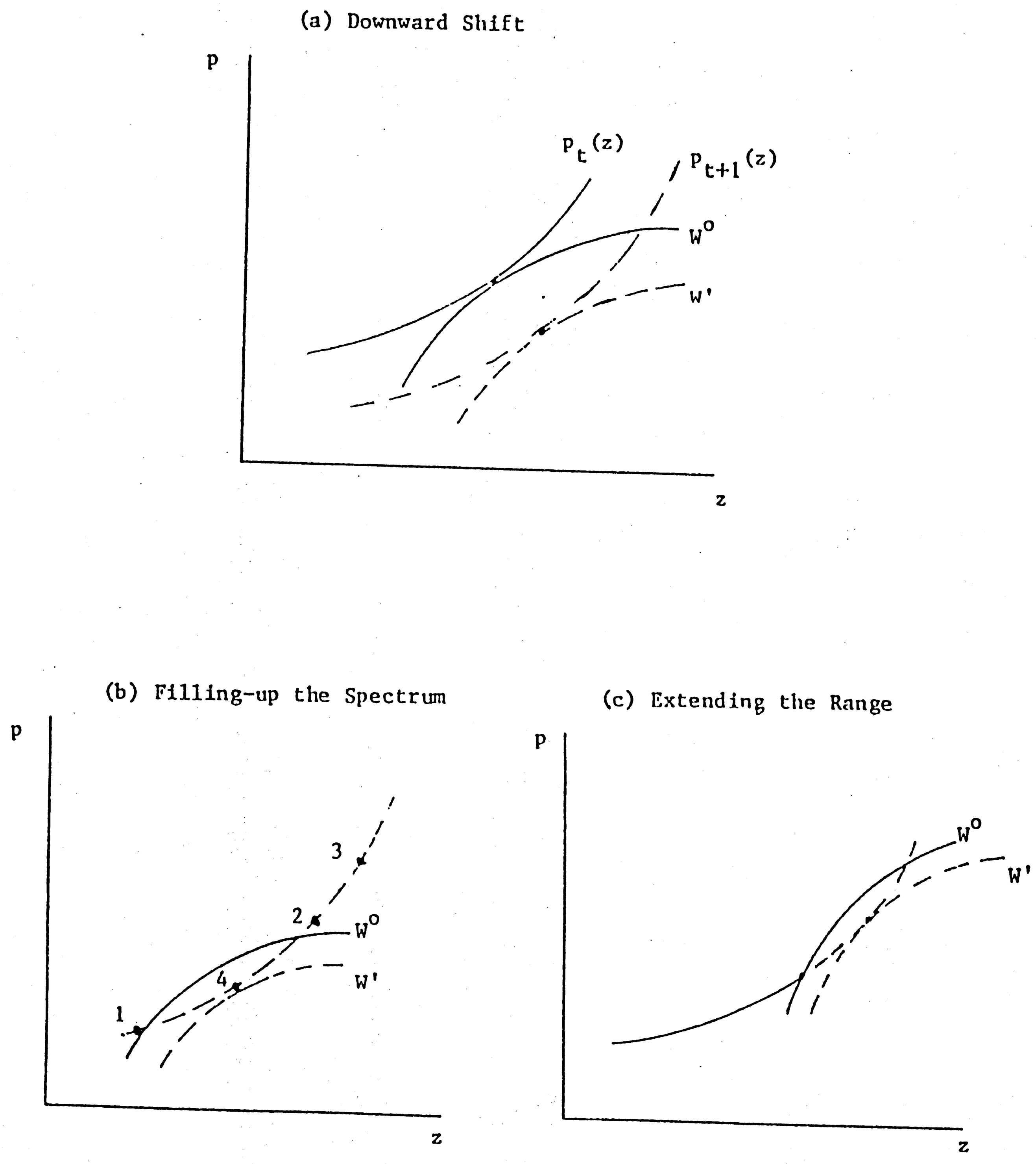
[17]Similarly, if z enters both in the utility function and in the hedonic equation as $\log z$, then a **proportional** change in the z of all brands (i.e. $z_{t+1} = \lambda z_t$, $\lambda > 1$, for all i) will render the same result.

Figure 1

<u>Alternative Effects of Innovation on Hedonic Price Functions</u>



leave no trace in the price index, whereas the actual gains may be substantial. Moreover, in the last two cases ΔW may be positive, and at the same time the hedonic-adjusted price index might actually **increase**, suggesting the occurance of **negative** innovations (for an empirical finding of that nature, see Alexander and Mitchel, 1985).

It should be clear that the three stylized types of changes described are equally legitimate as instances of product innovations, and a priori it would appear that they are equally likely. However, there is some evidence to the effect that the latter two are more prevalent during the initial stages of the 'product cycle', wherease the first tends to occur later on, in the wake of widespread imitation and price competition. If so, adjusting for quality changes with the aid of hedonic price functions may be a reasonable first approximation for well-established sectors, but not for tracing the emergence of new ones. As shown in Trajtenberg (1989a,b), the bulk of the gains from innovation in the case of CT scanners occured very early-on in the development of the field. If those results are typical (and there is some room to believe so), then the picture painted by hedonic-based price indices may systematically understate a great deal of the 'action' occuring in the technologically progressive sectors of the economy.

The potential for discrepancies are aggravated by two practical problems: the first is that the collection of data on new products by official agencies usually starts well after their initial stages, and second, that the norm is to chain-link them at the point of their inclusion in the index. In light of the above discussion it is clear that both practices, dictated to a large extent by pragmatic considerations, are very likely to further diminish the reliability of hedonic-based price indices as indicators of innovation.

5. ΔW-Based Indices versus Hedonic Price Indexes in the Case of CT Scanners

Having measured the welfare gains from innovation using the approach of section 2 in one particular case, namely CT Scanners, it is now possible to assess how far off-the-mark an hedonic-based price index would have been in this case, and thus get a sense for the extent to which prevalent indices might be presenting a distorted image of the dynamic performance of high tech sectors.

First, a few words about the innovation studied: Computed Tomography (CT) is a highly sophisticated diagnostic technology that produces cross-sectional pictures of internal organs of the body, using a special configuration of x-rays, detectors and computers. It has been hailed as one of the most remarkable medical innovations of recent times, comparable to the invention of radiography (the 1979 Nobel Prize in Medicine was awarded to the two scientists that pioneered the system). Originally developed at the british firm EMI in the early seventies, CT soon attracted some twenty other firms worlwide, and the fierce competition that ensued brought about a breathtaking pace of technical advance. The diffusion of the new systems proceeded very fast as well: first introduced in the US in 1973, by 1985 almost 60% of hospitals (with more than 100 beds) had at least one system installed. The pace of innovation in CT subsided in the mid-eighties, as the technology matured and ceded its dominant place to new technological developments, particulary to Magnetic Resonance Imaging. Two types of scanners were developed: head only, and whole-body systems (the latter appeared later, but they have dominated the scene ever since the mid-seventies). The price and technological evolution of the two types of scanners has been very different: head scanners become simpler and cheaper over time (particulary so since 1978), whereas body scanners exhibited a tremendous pace of technical advance and a corresponding steep rise in prices. Thus, I report separate figures for each type, as well as for all CT scanners.

Table 1 shows the estimates of ΔW_t and the mean prices (those figures are taken from Trajtenberg, 1989): notice that ΔW_t exceeds $\bar{p}_t$ during the first 3-4 years following the introduction of CT, and hence one can compute only the second index $\delta'_t \equiv \varphi_t/(1+\varphi_t) = \Delta W_t/(\Delta W_t + \bar{p}_t)$. That is, there were drastic technical advances in CT during the initial period (as reflected in the large values of ΔW_t), and hence the first index, requiring that $\Delta W_t < \bar{p}_{t-1}$, is not applicable in the present case. Notice that the index δ' indicates the occurance of 'negative innovations' (i.e. increases in 'real' prices) in head scanners in 1979, 1980 and 1982, in spite of a downward trend in nominal prices. This had to do with the shrinking of the set of head scanners offered in the market, as body scanners gained dominance.

The computation of hedonic indices can be done in various ways, of which the following were considered here: (a) weighted versus unweighted regressions (the weights being annual unit sales of each brand); (b) pooled regressions with dummy variables for each year, versus separate regressions for each pair of adjacent years (see Griliches 1971 for a discussion of the relative merits of each method). Table 2 presents the estimated hedonic equations pooling all years, weighted and unweighted (the regressions for adjacent years are not reported since there were too many of them). and the corresponding hedonic-based indices are computed in tables 3 and 4. The functional form in all cases is the double-log, and hence the coefficients of the yearly dummies, properly adjusted, can be taken as the 'pure' (or 'quality adjusted) price change, in percentage terms.[18]

The results of all four hedonic specifications considered are quite similar when contrasted with the ΔW-based index: the 'real' price reductions that occured in CT were much larger than what the hedonic method is able to uncover, particulary during the first few years. Table 5 shows that in a condensed way: if no correction is made at all, one would conclude that CT Scanners were about 2.5 times more expensive in 1982 than a decade earlier, and hence that we are significantly worse off on that account. Using the hedonic technique significantly alters that initial assesment: the quality-adjusted hedonic index goes down from 100 to 27, implying an average annual price **decrease** of 13%. Still, that is a far cry from the actual pace of technical advance that took place in CT: the ΔW-based index goes down from **10000 to** 7, implying a staggering real price reduction of **55%** per year on average! It is important to note that, if one were to start the measurements say, in 1977, the extent of the discrepancies would be greatly attenuated, as can be infered from the figures in italics in table 5. However, rather than finding comfort is those figures, they should serve as a warning, i.e. the

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[18]Denote the coefficient of the dummy for year t in a pooled hedonic regression as β_t ; the percentange 'pure' price change between year t-1 and t is computed as $\exp(\beta_t - \beta_{t-1})$. Recall that for small β's, $\exp \beta \cong \beta$, hence the common practice of taking just the differences $\beta_t - \beta_{t-1}$. In the present case, though, those differences are often quite large, and hence one should take indeed the exponent.

hedonic method may not do so badly when it comes to technologically mature industries, but it seems to be completely off mark early on, when it is needed the most.

Going back to tables 3 and 4, it is interesting to contrast the relative performance of the hedonic index for head versus body scanners. Notice that, starting in 1977, the hedonic indices for head scanners based on weighted regressions do not diverge that much from δ'. On the other hand, those for body scanners do extremely poorly, except for two years (1978 and 1982). This is no coincidence: as said before, even though there were some improvements in the attributes of head scanners after 1977, most of the 'action' in that segment of the market took the form of downward displacements of the hedonic price function, i.e. price reductions for only slightly altered systems. As argued in section 4.3, the hedonic technique is indeed quite appropriate in that case. Body scanners, on the other hand, kept getting better and more expensive (in the terms of section 4.3, that would correspond to 'extending the range'), a phenomenon that completely eludes the hedonic method.

Table 1

Computation of the ΔW-based Price Indices for CT Scanners

Year	Head Scanners ΔW	Head Scanners $\bar{p}$	Head Scanners δ'	Body Scanners ΔW	Body Scanners $\bar{p}$	Body Scanners δ'	All Scanners ΔW	All Scanners $\bar{p}$	All Scanners δ'
1974							4,391	370	-0.92
1975							875	372	-0.70
1976	994[a]	374	-0.73	1967[a]	471	-0.81	2,961	448	-0.87
1977	37	354	-0.09	724	573	-0.56	620	541	-0.53
1978	257	167	-0.61	15	620	-0.02	82	494	-0.14
1979	-10	154	+0.07	158	667	-0.19	108	515	-0.17
1980	-16	154	+0.12	83	739	-0.10	64	626	-0.09
1981	7	150	-0.04	190	827	-0.19	174	770	-0.18
1982	-3	150	+0.02	209	850	-0.19	195	804	-0.19

[a]Imputed figures.

ΔW: Social gains from innovation in CT Scanners, computed according to equations (4) and (1), in current prices.

$\bar{p}$: Weighted mean price (weights: annual unit sales).

δ': ΔW-based price change: $\delta'_t = -\Delta W_t/(\Delta W_t + \bar{p}_t)$.

Source of data on ΔW and $\bar{p}$: Trajtenberg (1989).

Notes to Table 2

In the headings: W means weighted regressions (annual unit sales as weights), and UnW stands for unweighted regressions.

The three attributes (speed, resolution and reconstruction time) are measured so that 'less is better' (e.g. speed is measured in seconds per scan, and hence the faster a scanner is, the better). Thus, we expect that their coefficients in the hedonic regressions will be negative. All three are in logs. 'Head' is a dummy variable for head scanners.

There are less observations in the weighted regressions, since some of the CT scanners had zero sales.

Table 2
Hedonic Price Regressions

	All Scanners W	All Scanners UnW	Body Scanners W	Body Scanners UnW	Head Scanners W	Head Scanners UnW
constant	8.12 (28.1)	7.99 (27.7)	6.73 (21.1)	6.9 (53.2)	6.25 (10.4)	6.78 (9.8)
Head Dummy	-.22 (-3.1)	-0.26 (-3.7)				
Speed	-0.22 (-9.0)	-0.19 (-8.6)	-0.14 (-13)	-0.15 (-8.8)	-0.04 (-0.7)	-0.10 (-1.7)
Resolution	-0.53 (-5.4)	-0.44 (-4.7)	-0.30 (-7.7)	-0.44 (-7.4)	0.35 (0.9)	0.11 (0.30)
Recon.Time	-0.05 (-2.2)	-0.06 (-3.5)	-0.03 (-3.5)	-0.05 (-3.7)	-0.12 (-2.3)	-0.10 (-2.5)
D74	0.07 (0.3)	-0.43 (-1.5)			0.15 (0.7)	0.09 (0.2)
D75	-0.49 (-2.0)	-0.54 (-2.0)	0.06 (0.2)	0.04 (0.3)	0.15 (0.5)	-0.24 (-0.6)
D76	-0.78 (-3.2)	-0.67 (-2.6)	0.13 (0.42)	0.13 (1.1)	0.06 (0.2)	-0.16 (-0.4)
D77	-0.95 (-3.9)	-0.84 (-3.2)	0.11 (0.34)	0.03 (0.3)	-0.005 (-0.0)	-0.28 (-0.7)
D78	-1.19 (-4.7)	-0.96 (-3.6)	0.10 (0.30)	-0.01 (-0.1)	-0.73 (-2.1)	-0.52 (-1.2)
D79	-1.28 (-5.0)	-1.05 (-3.9)	0.07 (0.21)	-0.03 (-0.2)	-0.82 (-2.3)	-0.88 (-1.9)
D80	-1.26 (-4.8)	-1.12 (-4.1)	0.10 (0.31)	-0.08 (-0.7)	-0.79 (-2.2)	-1.01 (-2.2)
D81	-1.20 (-4.4)	-1.06 (-3.9)	0.18 (0.56)	0.02 (0.16)	-0.83 (-2.2)	-1.03 (-2.2)
D82	-1.30 (-2.2)	-1.11 (-4.0)	0.09 (0.24)	-0.04 (-0.3)		-0.98 (-2.1)
Obs.	115	136	81	96	33	39
R^2	0.84	0.81	0.94	0.83	0.89	0.69

t-values in parenthesis (see notes on next page)

Table 3

'Quality-Adjusted' Price Changes: Hedonic versus ΔW-based Indices
All Scanners

Year	Hedonic: Pooled Unweighted	Hedonic: Pooled Weighted	Hedonic: Adjacent Unweighted	Hedonic: Adjacent Weighted	δ'_t
1974	-0.43	+0.07			-0.92
1975	-0.11	-0.34*	+0.03	+0.01	-0.70
1976	-0.12	-0.25*	+0.13	+0.03	-0.87
1977	-0.16	-0.16*	-0.05	+0.01	-0.53
1978	-0.11	-0.21*	-0.09	-0.17*	-0.14
1979	-0.09	-0.09	-0.08	-0.04	-0.17
1980	-0.07	+0.02	-0.08	+0.02	-0.09
1981	+0.06	+0.06	+0.06	+0.05	-0.18
1982	-0.05	-0.10	-0.08	-0.14	-0.19

*: Differences (with previous year) statistically significant ($\alpha = 0.05$ or better).

Table 4

'Quality-Adjusted' Price Changes: Hedonic versus ΔW-based Indices
Separate Figures for Head and Body Scanners

4.a Head Scanners

Year	Hedonic: Pooled Unweighted	Hedonic: Pooled Weighted	Hedonic: Adjacent Unweighted	Hedonic: Adjacent Weighted	δ'_t
1974	+0.09	+0.15			
1975	-0.28	0.00	-0.09		
1976	+0.08	-0.09	+0.10	+0.04	-0.73
1977	-0.11	-0.06	-0.10	-0.05	-0.09
1978	-0.21	-0.51*	-0.26	-0.43*	-0.61
1979	-0.30	-0.09	-0.17	-0.03	+0.07
1980	-0.12	+0.03	-0.19	+0.09*	+0.12
1981	-0.02	-0.03	-0.02	-0.04	-0.04
1982	+0.06		+0.06*		+0.02

4.b Body Scanners

Year	Hedonic: Pooled Unweighted	Hedonic: Pooled Weighted	Hedonic: Adjacent Unweighted	Hedonic: Adjacent Weighted	δ'_t
1975	+0.04	+0.06	+0.04	n.a.	n.a.
1976	+0.07	+0.05	+0.05*	+0.04*	-0.81
1977	-0.09	-0.03	-0.02	+0.02	-0.56
1978	-0.03	-0.01	-0.00	+0.01	-0.02
1979	-0.03	-0.03	-0.01	-0.03	-0.19
1980	-0.05	+0.03	-0.06	+0.01	-0.10
1981	+0.09*	+0.08*	+0.08	+0.07	-0.19
1982	-0.05	-0.09	-0.12	-0.14	-0.19

* Yearly differences statistically significant ($\alpha = 0.05$ or better).

Table 5

Comparing Various Indices: All CT Scanners

Year	Nominal Index[a]		Hedonic[b]		ΔW-based	
1973	10,000		10,000		10,000	
1974	11,940		10,770		800	
1975	12,000		6,130		240	
1976	14,450		4,600		31	
1977	17,450	*100*	3,850	*100*	15	*100*
1978	15,940	*91*	3,050	*79*	13	*87*
1979	16,610	*95*	2,780	*72*	11	*73*
1980	20,190	*116*	2,840	*74*	10	*67*
1981	24,840	*142*	3,020	*78*	8	*53*
1982	25,940	*149*	2,730	*71*	7	*47*

[a] $\bar{p}_t / \bar{p}_{73}$, where $\bar{p}_t$ is the weighted mean price in year t.

[b] The Hedonic Index is based on the weighted pooled hedonic regression.

References

Alexander, Arthur J., and Bridger M. Mitchell. 1985. "Measuring Technological Change of Heterogeneous Products." **Technological Forecasting and Social Change** 27(2/3):161-195.

Baily, Martin N. and Robert J. Gordon. 1988. "The Productivity Slowdown, Measurement Issues, and the Explosion of Computer Power". **Brookings Papers on Economic Activity**, 2, 347-431.

Deaton, Angus, and John Muellbauer. 1980. **Economics and Consumer Behavior**. Cambridge: Cambridge University Press.

Diewert, Erwin W. 1987. "Index Numbers". **The New Palgrave: A Dictionary of Economics**, Vol. 2. J.Eatwell, M. Milgate and P. Newman (eds.), London, Macmillan Press, 767-780.

Epple, Dennis. 1987. "Hedonic Prices and Implicit Markets: Estimating Demand and Supply Functions for Differentiated Products." **Journal of Political Economy** 95(1):59-80.

Fisher, Franklin M., and Karl Shell. 1972. **The Economic Theory of Price Indices: Two Essays on the Effects of Taste, Quality, and Technological Change**. New-York: Academic Press.

Griliches, Zvi. 1958. "Research Costs and Social Returns: Hybrid Corn and Related Innovations." **Journal of Political Economy** 66(5):419-431.

__________ ed. 1971. **Price Indexes and Quality Change**. Cambridge, Massachusetts: Harvard University Press.

Krantz, D., D. Luce, P. Suppes, and A. Tversky. 1971. **Foundations of Measurement**, Vol.1. New-York: Academic Press.

Lancaster, Kelvin J. 1971. **Consumer Demand: A New Approach**. New-York and London: Columbia University Press.

__________ 1979. **Variety, Equity, and Efficiency**. New York: Columbia University Press.

McFadden, Daniel. 1981. "Econometric Models of Probabilistic Choice." In **Structural Analysis of Discrete Data with Econometric Applications**, eds. C. Manski, and D. McFadden. Cambridge, Massachusetts: The M.I.T. Press.

Muellbauer, John. 1974. "Household Production Theory, Quality and the 'Hedonic Technique'." **American Economic Review** 64:977-994.

Rosen, Sherwin. 1974. "Hedonic Prices and Implicit Markets: Product Differentiation in Pure Competition." **Journal of Political Economy** 82(1):34-55.

Scherer, Frederic M. 1984. "Using Linked Patent and R&D Data to Measure Interindustry Technology Flows." In **R&D, Patents, and Productivity**, ed. Z. Griliches. Chicago: Chicago University Press.

Trajtenberg, Manuel. 1979. "Quantity is All very Well But Two Fiddles Don't Make a Stradivarius - Aspects of Consumer Demand for Characteristics." The Maurice Falk Institute for Economic Research in Israel, Discussion Paper No. 1008.

___________. 1987. "Patents, Citations and Innovations: Tracing the Links". **The National Bureau of Economic Research**, Working Paper # 2457, December.

___________. 1989a. "The Welfare Analysis of Product Innovations, with an Application to Computed Tomography Scanners". **Journal of Political Economy**, April, 97(2), 444-479.

___________. 1989b. **The Economic Analysis of Product Innovations - The Case of CT Scanners**. Cambridge, Mass: Harvard University Press, forthcoming.

Triplett, Jack E. 1975. "The Measurement of Inflation: A Survey of Research On the Accuracy of Price Indexes." In **Analysis of Inflation**, ed. P. H. Earl. Lexington, Massachusettes: Lexington Books.

APPENDIX

Incorporating the hedonic price function into the MNL model

The discussion in section 2 above overlooked an important feature of markets for differentiated products, namely, the fact that prices and attributes usually exhibit a systematic relationship, embedded in the hedonic price function:

(A.1) $$p_i = p(z_i) + \tilde{p}_i$$

where $p(z_i)$ is the systematic component, and $\tilde{p}_i$ an i.i.d. error term (the 'residual price'). The existence of such a relationship poses a serious multicollinearity problem in the estimation of the choice probabilities of equation (3): since both price and the vector z_i appear there as explanatory variables, their individual coefficients cannot be estimated with any precision. The solution suggested here involves incorporating the hedonic function into the consumers' indirect utility function (as a sort of budget constraint), and providing the latter with a more specific structure.

Substituting (A.1) for p_i in V_i, and ignoring y and h,

$$V_i = -\alpha[p(z_i) + \tilde{p}_i] + \phi(z_i) = \phi(z_i) - \alpha p(z_i) - \alpha\tilde{p}_i$$

or, defining $V^n(z_i) \equiv \phi(z_i) - \alpha p(z_i)$,

(A.2) $$V_i = V^n(z_i) - \alpha\tilde{p}_i.$$

where the term $V^n(z_i)$ can be interpreted as the 'net utility' conferred by product i (that is, net of the **expected** price of the product). Thus, the behavior of consumers is now seen to depend upon z_i and $\tilde{p}_i$, rather than upon z_i and p_i. In other words, given the existence of a hedonic function, p_i largely replicates the information already conveyed by z_i. Therefore, only the component of price that is orthogonal to z_i, $\tilde{p}_i$, can affect behavior, qualifying as a legitimate explanatory variable in the choice model.

In order for (A.2) to offer an actual solution to the multicollinearity problem, $V^n(z)$ needs to be given more structure. This is easly done with the aid of the following straightforward proposition: $V^n(z)$ can be closely approximated by the sum of a linear and a quadratic form, provided only that it has an interior maximum. More formally, $V^n(z) \cong z'\beta + z'Gz$, where G is a symmetric matrix, if there is a $z^* > 0$, such that: $z^* = \arg\max V^n(z)$. When this is so, the approximation $(z'\beta + z'Gz)$ obtains readily from a second-order Taylor expansion about z^*. Normally we would expect $\phi(z)$ to be concave (or quasi-concave), and the hedonic function to be convex (as has been found in many empirical studies), in which case $V^n(z)$ would necessarily meet the required condition. The suggested specification of the 'net utility' leads to the following model,

(A.3)
$$\pi_i = \exp V_i / \Sigma \exp V_j,$$
$$V_i = z_i'\beta + z_i'Gz_i - \alpha\tilde{p}_i,$$
$$\tilde{p}_i = p_i - p(z_i)$$

which can be estimated simultaneously, or using a two-stage procedure (i.e. first estimate the hedonic price function and compute the residuals $\tilde{p}_i$; second, enter $\tilde{p}_i$ as an independent variable in π_i and estimate the MNL model). If each choice set (and hence each hedonic price function) is determined prior to the beginning of period t and does not change in the course of the period, then the latter method is appropriate; otherwise a simultaneous equations framework is required.