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The Measurement of Quality Change from Vintage Price Data

1. Introduction

Under some circumstances, the quality of a capital good can be measured unambiguously by a single numerical index. When this is possible, and when the type of capital good under consideration is traded in a secondhand market, it is natural to look for a method for deducing the relative qualities of capital goods of different vintages or model years from the corresponding relative prices in the secondhand market. This proposal is made particularly attractive by the fact that if the price of each vintage is observed N times, its ratio to the price of the next earlier or later vintage is observed $N - 1$ times. This permits the calculation of the relative quality of two successive vintages as an appropriate average of the $N - 1$ separate observations. Something can then be said about the statistical properties of the resulting quality index, and formal statistical tests of hypotheses about quality change can be carried out.

The only difficulty with this proposal is that the difference between the prices of two capital goods of different ages is determined not just by the difference in their inherent qualities but also by a pure age effect, namely depreciation. Comparison between prices observed at different times can eliminate the depreciation effect, but only at the cost of introducing the influence of the changing price level. In order to measure quality change from secondhand market data, some method for disentangling it from the effects of depreciation and changes in the price level is needed.

This paper is devoted to the theoretical and empirical study of the problem just mentioned. In Section 2, some theoretical aspects of the behavior of secondhand markets are discussed. Conditions for the existence

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of an overall measure of capital efficiency are mentioned, and the definition of a quality index as a special restriction on the efficiency index is proposed. The quality index (or index of embodied technical change) is shown to be unambiguously defined except for its trend or average rate of growth, which cannot be measured from secondhand market data in the absence of additional information.

In Section 3 the regression equation developed in Section 2 is applied to data on the prices of used pickup trucks. The trend in quality change is arbitrarily set to zero, so only departures from a constant rate of growth are measured. The results are in close accord with Triplett's findings for automobiles (1966), although based on an entirely different method; they suggest that the rate of quality improvement was much higher from 1955 to 1960 than from 1961 to 1966. Various hypotheses about the path of quality change and the relation between the two makes studied (Chevrolet and Ford) are tested. The hypothesis of geometric or declining balance depreciation is tested and rejected.

In Section 4, two methods for estimating the trend of quality change are discussed and tested. The first is due to Cagan (1965)[1] and consists in identifying vintages that are apparently functionally identical and adjusting the trend of the quality index so that it has the same value for these vintages. The second is to express the quality index as a function of observed characteristics and to estimate the parameters of that function from the price data. It is essentially the well-known hedonic method applied to the matrix of prices for a single make in place of the vector of prices of many makes. The results of both of these methods are quite similar; the quality index rises rapidly from 1955 to 1960 and falls slightly from 1961 to 1966, again in conformity with Triplett's results for automobiles.

Finally, in the last section the quality-corrected price index for pickup trucks derived in this study is compared to various other related indexes. The suggestion is made that the index derived from the secondhand market may measure actual transaction prices for new trucks more satisfactorily than does the list price or the Wholesale Price Index for trucks. The quality-corrected index of this study shows a steady upward movement from 1963 to 1966, while the official index and the list price remain roughly constant. No support is given in this study to the hypothesis that the upward movement in the unit price of pickup trucks from 1961 to 1967 was the result of quality improvement rather than inflation.

1. In many respects the whole of the present paper can be regarded as a formalization and refinement of Phillip Cagan's work.

2. The Behavior of Secondhand Markets for Capital Goods

The natural starting point in our discussion of secondhand markets is the familiar hypothesis that the price of a capital good is equal to the present value of its future services:

$$p_{t,\tau} = \sum_{s=0}^{N-\tau-1} \left(\frac{1}{1+r}\right)^s x_{t+s,\tau+s}. \tag{2.1}$$

Here $p_{t,\tau}$ is the price at time t of a capital good of age τ, r is the interest rate (assumed to remain constant over time), and $x_{t,\tau}$ is the value at time t of the services of a capital good of age τ. The implications of this hypothesis, without any further restrictions, were studied many years ago by Harold Hotelling in an important paper (1925).

Our goal here is to construct a restricted form of equation (2.1) with the property that the familiar parameters of capital measurement—deterioration and technical change—appear in it explicitly. We begin by separating the value of the services of a capital good into a price and a quantity:

$$x_{t,\tau} = \hat{p}_t z_{t,\tau}. \tag{2.2}$$

Here $\hat{p}_t$ is the rental price of one unit of capital services, and $z_{t,\tau}$ is the number of units of capital services provided by a capital good of age τ at time t. Separation in this way does not impose any mathematical restriction on $x_{t,\tau}$, and can be done in any number of arbitrary ways. A leading question in capital theory is whether or not there is a natural method for separating the value of capital services into a price and a quantity. By a natural method we mean a method for measuring the quantity of capital services that permits the calculation of a meaningful total quantity of the services of capital goods of all ages. Furthermore, we require that the quantity of services attributed to a particular capital good be independent of the circumstances in which it is used in production; in particular, it should be independent of the quantity of other factors employed and of the quantity of capital goods of different ages available. In other words, the index $z_{t,\tau}$ should be a purely technical measure of the relative efficiency of capital goods, unaffected by economic variables.[2]

2. The conditions under which a capital aggregate can be formed have been studied very intensively at the theoretical level; see Fisher 1965 for a definitive treatment and a bibliography of previous work. In vintage production functions with constant returns to scale, the basic theorem of capital aggregation establishes that a capital aggregate exists if and only if the marginal product of capital of age τ at time t has the fixed ratio $z_{t,\tau}/z_{t,0}$ to the marginal product of new capital at time t. This can be extended to intertemporal comparisons by considering the (hypothetical) problem of aggregating new capital of different vintages. By the same theorem, this can be done if and only if the marginal product of capital of vintage t has the fixed ratio $z_{t,0}$ to the marginal product of capital of the first vintage. The latter is normalized at 1: $z_{1,0} = 1$. Taken together, these conditions imply the existence of $z_{t,\tau}$.

If we suppose that such an index exists, it has a strong implication for the behavior of rental prices at any point in time; since the services of old and new capital goods are perfect substitutes, the rental prices of capital goods must stand in the fixed proportions dictated by their relative efficiencies. In this case, there is a well-defined measure of rental per unit of capital, independent of the age of the capital supplying the services. The separation of price and quantity expressed in equation (2.2) was written with this in mind; $\hat{p}_t$ does not depend on age, τ.[3]

The index $z_{t,\tau}$ combines the influence of deterioration (decline in efficiency as capital ages), embodied technical change (increasing efficiency for later vintages of capital), and disembodied technical change (increasing efficiency of all capital as time passes). Implicit in most discussions of quality change and capital measurement is the assumption that these processes take place independently, so that it is sensible to speak of an index of deterioration, say Φ_τ, an index of embodied technical change, b_t, and an index of disembodied technical change, d_t. The hypothesis of independence is expressed mathematically by putting the efficiency index $z_{t,\tau}$ equal to the product of the three indexes:

$$z_{t,\tau} = \Phi_\tau b_{t-\tau} d_t. \tag{2.3}$$

This is a strong restriction and one that can be tested with the data available.

At this point a grave difficulty arises. The comprehensive efficiency index $z_{t,\tau}$ is a characteristic of the production function and could be measured to any degree of accuracy by a suitable set of experiments. But even if it were known exactly, and if it obeyed the independence assumption stated earlier, it would not be possible to deduce the indexes Φ_τ, b_v, and d_t from it. The difficulty is the following: Suppose it is true that

$$z_{t,\tau} = \Phi_\tau b_{t-\tau} d_t. \tag{2.4}$$

Then it is also true that

$$z_{t,\tau} = \Phi^*_\tau b^*_{t-\tau} d^*_t, \tag{2.5}$$

3. The relation between capital aggregation and the rental price of capital was studied by the present author in an earlier paper (1968). Much of what follows in this section is adapted from that paper.

where the indexes with *'s are different from their counterparts in equation (2.4) in every period other than the base period. In other words, there is an ambiguity in separating the total change in efficiency into components of deterioration, embodied technical change, and disembodied technical change. The precise form of the ambiguity is the following: If $\Phi_\tau b_{t-\tau} d_t$ is one way to write $z_{t,\tau}$, then equally valid alternatives are provided by

$$\Phi^*_\tau = B^\tau \Phi_\tau \tag{2.6}$$

$$b^*_{t-\tau} = B^{t-\tau} b_{t-\tau} \tag{2.7}$$

and

$$d^*_t = B^{-t} d_t, \tag{2.8}$$

where B is any positive number.[4] So in spite of the fact that the unrestricted efficiency index $z_{t,\tau}$ is an unambiguous measure, the conventional factorization of the efficiency index into deterioration, embodied technical change, and disembodied technical change contains a serious ambiguity. Information from the production function (all the relevant information is contained in $z_{t,\tau}$) can be used to find indexes Φ_τ, b_v and d_t, but it cannot distinguish between these and the alternatives given in equations (2.6), (2.7), and (2.8). For B taken to be greater than one, these equations show that slower deterioration, faster embodied technical change, and slower disembodied technical change are an equally valid description of the characteristics of the production function. In a world in which embodied technical change takes place smoothly over time at a constant rate of growth (that is, b_v is an exponential function of v), the notion of embodiment can be dispensed with altogether by an appropriate choice of B. In Hall 1968 I suggested that the appropriate way to eliminate the ambiguity in the conventional view of deterioration and technical change is to adopt an arbitrary normalization of any of the three indexes by setting it to 1 at a second point. The easiest such normalization for our present purposes is to set the index of embodied efficiency to 1 at the end of the period of observation as well as at the beginning. From the point of view of the study of production functions, this normalization is inconsequential since it does not affect $z_{t,\tau}$. On the other hand, the quality-corrected price index we derive below is seriously affected by the choice of normalization. If it is to have any meaning, something better than an arbitrary distinction between embodied and disembodied technical change must be found.

4. For a proof that this is the only ambiguity, see Hall 1968. There, B is written e^β.

This raises the question of whether there is additional information available that might allow us to make the distinction.[5] We have already established that no information about how capital is used in production will allow us to escape the ambiguity—all such information is contained in the index $z_{t,\tau}$, and that is not enough. However, there is another source of information that we have not drawn upon so far. If embodied technical change is associated with change in the characteristics of the capital goods, then information about those characteristics can be brought to bear on the problem of separating embodied from disembodied technical change. The prospects for empirical success in such a procedure are quite good, since this information is used to estimate only a single parameter, namely the undetermined coefficient B in equations (2.6), (2.7), and (2.8).

Returning now to the basic present value relationship thought to characterize markets for secondhand capital goods, we have, after substituting the proposed restriction on rental values,

$$p_{t,\tau} = \sum_{s=0}^{N-\tau-1} \left(\frac{1}{1+r}\right)^s \Phi_{\tau+s} b_{t-\tau} d_{t+s} \hat{\rho}_{t+s}. \tag{2.9}$$

This assumes foresight with respect to the future behavior of disembodied technical change, d_{t+s}, and the rental price, $\hat{\rho}_{t+s}$. An alternative assumption, perhaps more realistic and certainly more convenient, is that all participants in the market have static expectations about d_{t+s} and $\hat{\rho}_{t+s}$.[6] Then

$$p_{t,\tau} = b_{t-\tau} d_t \hat{\rho}_t \sum_{s=0}^{N-\tau-1} \left(\frac{1}{1+r}\right)^s \Phi_{\tau+s}. \tag{2.10}$$

The separate components of the product $d_t\hat{\rho}_t$ are not econometrically identifiable in this equation. In economic terms, disembodied technical change has no differential effect on capital goods of different ages at the same point in time. Its effect over time cannot be distinguished from the effect of changes in the rental price over time. In short, nothing about disembodied technical change can be deduced from secondhand market data. We can, however, estimate the product, $\rho_t = d_t\hat{\rho}_t$, and interpret

5. At this point we depart from Hall 1968.

6. The errors made in assuming a constant interest rate and static expectations for $\hat{\rho}_t$ are self-canceling to the extent that departures are caused by pure inflation. The assumptions here are equivalent to assuming a constant *real* interest rate and static expectations for $\hat{\rho}_t$ in real terms.

it as the rental price of capital services uncorrected for disembodied technical change.[7] Then we have

$$p_{t,\tau} = b_{t-\tau} \rho_t \sum_{s=0}^{N-\tau-1} \left(\frac{1}{1+r}\right)^s \Phi_{\tau+s}. \tag{2.11}$$

This is our basic behavioral equation, stated in terms of the parameters of capital measurement. A change of variables puts it in an alternative form in terms of the parameters of price measurement. We let

$$\bar{p}_t = \rho_t \sum_{s=0}^{N-1} \left(\frac{1}{1+r}\right)^s \Phi_s; \tag{2.12}$$

this is a price index for new capital goods corrected for quality change (embodied technical change). Second,

$$D_\tau = \frac{\displaystyle\sum_{s=0}^{N-\tau+1} \left(\frac{1}{1+r}\right)^s \Phi_{\tau+s}}{\displaystyle\sum_{s=0}^{N-1} \left(\frac{1}{1+r}\right)^s \Phi_s}; \tag{2.13}$$

this is an index of *depreciation*, the decline in the price of a secondhand capital good as it ages. Under the special hypothesis of geometric deterioration,

$$\Phi_\tau = (1-\delta)^\tau, \qquad N = \infty, \tag{2.14}$$

D_τ has the same geometric form, $(1-\delta)^\tau$, so the deterioration index and the depreciation index are identical. In every other case, however, the distinction between deterioration and depreciation is an important one. The failure to make this distinction has led to a certain amount of confusion in the literature on capital measurement.

In the new parametrization, our behavioral equation is

$$p_{t,\tau} = \bar{p}_t b_{t-\tau} D_\tau. \tag{2.15}$$

That is, the observed price of a used capital good is the underlying quality-corrected price index $\bar{p}_t$, adjusted for quality as given by the index $b_{t-\tau}$ and depreciation as given by the index D_τ. We should note that this very simple relationship holds only under the assumption of

7. This is a sensible quantity to measure in its own right, since it excludes changes in efficiency due to changes in the method of using capital and includes changes attributable to the capital good itself.

static expectations. Investigation of more sophisticated hypotheses about expectations could only be carried out in the original present value equation.

For convenience in estimation, we assume that a random disturbance enters equation (2.15) multiplicatively, so that by taking logs, we get

$$\log p_{t,\tau} = \log \bar{p}_t + \log b_{t-\tau} + \log D_\tau + u_{t,\tau}. \tag{2.16}$$

The regression coefficients are the logs of the three indexes, and all of the right-hand variables are dummy variables. Two index normalizations are required; we use $D_1 = 1$ and $b_0 = 1$, implying that depreciation is measured relative to one-year-old capital goods and that quality is measured relative to the quality of vintage 0. In addition, we require a second normalization on the quality index; we use $b_{T-1} = 1$, where $T - 1$ is the last vintage observed, so that no net change in quality takes place over the period of observation.

An example may be useful to clarify this procedure. If $T = 3$ and $N = 4$, and price data from the secondhand market, $p_{t,\tau}$, are available for $\tau = 1, 2, 3$ and $t = 1, 2, 3$ (i.e., the prices of new capital goods are not available, as is the case in the present study), and if the observation matrix is stacked by rows to form a column vector, then the matrix of right-hand variables is

$$X = \begin{array}{cccccccc|c} \bar{p}_1 & \bar{p}_2 & \bar{p}_3 & D_2 & D_3 & b_{-2} & b_{-1} & b_1 & b_2 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 \end{array} \tag{2.17}$$

Above each column is indicated the parameter whose log is the regression coefficient corresponding to that column. The normalizations are imposed simply by excluding the columns for the parameters normalized at unity, since their coefficients are zero. The excluded column for b_2 is shown just to the right of the matrix. It is useful to show that it is a linear combination of the columns of X, so that its inclusion in an attempt to measure the trend in quality change would cause the regression calculation to break down If $X(\bar{p}_1)$ is the column corresponding to $\bar{p}_1$, $X(D_2)$ to D_2, and so forth, then

$$X(b_2) = \tfrac{1}{2}[X(\bar{p}_2) + 2X(\bar{p}_3) - X(D_2) - 2X(D_3) + 2X(b_{-2}) + X(b_{-1}) - X(b_1)]. \tag{2.18}$$

This shows that the trend is not identified in this regression, confirming the analysis of the first part of this section.

3. Estimates of Efficiency Parameters for Half-Ton Pickup Trucks—Unrestricted Quality Change

Pickup trucks are well-suited to the kind of analysis just described. They are a standardized product traded in an active, competitive second-hand market, with relatively low transactions costs. In the period studied, 1955 to 1966, they underwent a number of minor design changes of the sort presumably described by our notion of quality change, but none was so major as to cast serious doubt on our capital-aggregation assumption that the services of old trucks are perfect substitutes for the services of new trucks.

Data for the average market prices in April of used pickup trucks were obtained from the National Automobile Dealers Association *Official Used Car Guide*[8] for the years 1961 to 1967, covering model years 1955 to 1966. Two makes were studied: Chevrolet (model 3104 for 1955 to 1959, C1404 for 1960 to 1966) and Ford (model F-100 in all years). For both makes, the older style pickup body (Stepside for Chevrolet, Flareside for Ford), the 6-cylinder engine of 230- to 250-cubic-inches displacement, and the 110- to 115-inch wheelbase were studied. Prices for models of the six previous years are published in the *Guide* and are reproduced in Table 8.1. Apparently because the market in very new trucks is quite thin, prices for trucks of the current model year are not available in April (The 1968 *Guide* was not used at all because the latest model reported was 1966). Consequently, this study does not cast any light on the important question of how much a truck depreciates in its first year.

Our first set of results is for the simplest reasonable specification. We assume that $b_v = 1$ for all vintages. In view of the normalization requirement, we can see that this restriction is compatible with smooth exponential quality change at any positive or negative rate. The improvement in

8. I am grateful to Zvi Griliches for making his back copies of the publication available to me.

Table 8.1. Prices of Used Pickup Trucks

	Chevrolet					
	Age (years)					
Model Year	1	2	3	4	5	6
1961	$1575	$1260	$1040	$ 910	$690	$500[a]
1962	1640	1375	1070	865	710	545
1963	1640	1350	1110	850	670	510
1964	1720	1405	1185	1010	745	550
1965	1625	1400	1185	1020	875	655
1966	1765	1415	1205	1005	850	700
1967	1575	1420	1205	1000	820	710
	Ford					
1961	$1550	$1230	$1065	$870	$670	$525
1962	1660	1340	1075	860	700	520
1963	1630	1345	1095	885	715	550
1964	1710	1405	1150	995	765	585
1965	1655	1385	1150	985	815	640
1966	1745	1470	1210	1005	820	685
1967	1600	1440	1210	1000	825	700

[a] Average of two models.

the fit that we obtain later in the study by estimating parameters of quality change is attributable to the presence of nonexponential quality change, that is, to changes in the trend in quality change.

Results for this simple specification are given in Table 8.2. Twelve parameters are estimated: 7 prices and 5 points on the depreciation function. These results suggest, not surprisingly, that the view is close to the truth that capital depreciation is the principal determinant of prices in the used truck market. The standard errors of the regressions are 6.0 percent for Chevrolets and 4.2 percent for Fords. The size of the standard errors of the estimates of the parameters suggests that they are measured with considerable accuracy. The covariances of the estimates of the prices are all positive in both regressions, so that differences between the rental rates have standard errors only slightly larger than those of the estimates themselves. As a result, relatively powerful tests of hypotheses about changes in the prices can be made. The most interesting of these is the test for inflation over the whole period. The null hypothesis of no inflation

Table 8.2. Regression Results for Constant Rate of Quality Change

Year	Price Index: Chevrolet log $\bar{p}_t$	Chevrolet $\bar{p}_t$	Ford log $\bar{p}_t$	Ford $\bar{p}_t$	Age (years)	Depreciation index: Chevrolet log D_τ	Chevrolet D_τ	Ford log D_τ	Ford D_τ	Summary statistics	Chevrolet	Ford
1961	7.318 (0.032)	\$1508	7.314 (0.022)	\$1501	1	0 —	1.000	0 —	1.000	Standard error	0.060	0.042
1962	7.355 (0.032)	1564	7.345 (0.022)	1549	2	−0.181 (0.032)	0.834	−0.184 (0.022)	0.832	Sum of squared residuals	0.10638	0.05243
1963	7.334 (0.032)	1532	7.364 (0.022)	1577	3	−0.367 (0.032)	0.693	−0.373 (0.022)	0.688	R^2	0.980	0.990
1964	7.419 (0.032)	1667	7.428 (0.022)	1683	4	−0.552 (0.032)	0.576	−0.561 (0.022)	0.571			
1965	7.467 (0.032)	1749	7.444 (0.022)	1710	5	−0.771 (0.032)	0.463	−0.780 (0.022)	0.459			
1966	7.489 (0.032)	1788	7.487 (0.022)	1785	6	−1.027 (0.032)	0.358	−1.016 (0.022)	0.362			
1967	7.466 (0.032)	1747	7.473 (0.022)	1760								

in that case is $\bar{p}_7/\bar{p}_1 = 1$ (i.e., $\log \bar{p}_7 - \log \bar{p}_1 = 0$); the alternative hypothesis is $\bar{p}_7/\bar{p}_1 > 1$. For Chevrolets, estimated inflation, $\bar{p}_7/\bar{p}_1$, is 14.7 percent with standard error 3.4 percent. The corresponding t-statistic is 4.3, causing us to reject the null hypothesis at any reasonable level of significance. The estimate of inflation for Fords is 15.9 percent with standard error 2.4 percent, so the null hypothesis is even more emphatically rejected. Our conclusion is that if there has been no quality change in pickup trucks over the period 1955 to 1966, there certainly has been inflation in their prices between 1961 and 1967.

Since the depreciation function is also estimated in these regressions, any amount of smooth exponential quality change is compatible with the results just presented. If B^v is the true index of quality, then our estimates can be restated to take account of that fact in the following way: Estimated prices should be $\bar{p}_t/B^t$ and estimated depreciation should be $B^\tau D_\tau$, where $\bar{p}_t$ and D_τ are the estimates from the regressions just presented for the normalization of no quality change. Thus our conclusion that $\bar{p}_7$ is greater than $\bar{p}_1$, initially thought to indicate inflation in the cost of pickup trucks, might alternatively be attributable to quality change. This is the familiar claim that the observed inflation in many products actually reflects quality improvement. As long as we restrict our attention to data on the *efficiency* of capital goods, we are unable to test this optimistic view of inflation, exactly because we cannot separate changes in efficiency unambiguously into embodied and disembodied components. Information about the *characteristics* of capital can test this view, however. We shall return to this point in section 4; evidence presented there indicates fairly strongly that the optimistic view is incorrect and that a substantial amount of inflation took place over the period.

In the results presented above, the arbitrary normalization $bT = 1$ was imposed. In addition, a substantive restriction was imposed on b_v, namely that $b_v = 1$ for all vintages. Our next set of results relaxes the second restriction while keeping the normalization.[9] Departures of the estimates of $\log b_v$ (for $v = -4, \ldots, 0, 2, \ldots, 6$) from zero indicate *nonexponential* quality change. The results, shown in Table 8.3, suggest that quality change in pickup trucks has been far from exponential. In 5 out of 10 years for Chevrolets and 8 out of 10 for Fords, the estimated coefficient of the log of quality is more than two standard errors smaller or larger

9. The reader should be warned that the quality coefficient for the 1966 model is estimated from a single observation in these and all subsequent results. Since that observation was a year of distress in the market for used cars and trucks (1967), the quoted standard error probably understates the true standard error.

than zero. The null hypothesis that each coefficient is zero (purely exponential technical change) can be tested against the alternative hypothesis that some are different. The resulting F-statistic[10] is 6.1 with 20 and 40 degrees of freedom; the critical point in the F-distribution at the 0.05 level of significance is 1.8, so the null hypothesis is rejected decisively for both makes considered together (it is also rejected for each make separately). We conclude that in the microeconomic data under consideration, quality change does not proceed smoothly with the same upward trend over time, in spite of the fact that it is generally thought to do so in the aggregate.

The results in Table 8.3 suggest that the pace of quality change slowed substantially after 1960. The arbitrary normalization requires that no quality change take place between 1960 and 1966, so no statement can be made about its overall rate. A striking difference between the results in Table 8.3 and those in Table 8.2 is that the strong evidence of inflation in the earlier results is not supported at all when the restriction of purely exponential technical change is relaxed. As we shall see in section 4, there is some evidence that the normalization used in these estimates (that the efficiency of a one-year-old 1966 truck was the same as the efficiency of a one-year-old 1960 truck), actually overstates the trend of quality change. Note that the rate of quality change between 1960 and 1965 appears to have been significantly positive; it is a sudden drop in estimated efficiency in the 1966 models that makes the estimates meet the arbitrary normalization.

An indirect test of the validity of these results is provided by the reasonable assumption that Chevrolets and Fords are essentially perfect substitutes. If this is so, their prices should move in fixed proportion. The ratio between the two prices is shown in Table 8.3. There it appears that Chevrolets have become progressively cheaper per unit of capital over the period, in comparison to Fords. But this is not consistent with our assumption—the unit of capital is the one-year-old 1960 model in both cases, so every year after that (if the correction for technical change is

10. Tests of this and succeeding hypotheses are based on the statistic

$$F = [(N - 1)T - k_1]\,[Q_1 - Q_0]/[(k_1 - k_0)Q_0]$$

where Q_0 is the sum of squared residuals from the regression without the restriction, k_0 is the number of parameters estimated in the restricted regression, and k_1 is the number of parameters in the unrestricted regression. This statistic has the F-distribution with $k_1 - k_0$ and $(N - 1)T - k_1$ degrees of freedom, under the null hypothesis. In the absence of constraints across makes, Q_0 and Q_1 are calculated as the total sum of squared residuals for the corresponding separate regressions. Implicit in this procedure is the assumption that the variances of the disturbances are the same for both makes.

correct) the prices should stand in the same proportion. This suggests that it would be useful to set up a model in which the constraint is imposed that Chevrolets and Fords are perfect substitutes. This is particularly interesting because it permits us to estimate the quality of Fords of every vintage, including those coefficients previously normalized at unity. The resulting index gives the quality of Fords relative to the quality of the 1960 Chevrolet. An arbitrary normalization for the 1966 Chevrolet is retained; since the 1966 Ford is treated as a perfect substitute for the Chevrolet of that year, the quality coefficient for the 1966 Ford measures

Table 8.3. Regression Results for Unrestricted Quality Change and Unrestricted Depreciation (master model)

	Index of quality			
	Chevrolet		Ford	
Vintage	log b_v	b_v	log b_v	b_v
1955	−0.352 (0.061)	0.703	−0.245 (0.043)	0.783
1956	−0.236 (0.047)	0.790	−0.219 (0.033)	0.803
1957	−0.186 (0.038)	0.830	−0.140 (0.026)	0.869
1958	−0.177 (0.030)	0.838	−0.105 (0.021)	0.900
1959	−0.100 (0.025)	0.905	−0.061 (0.017)	0.941
1960	0 —	1.000	0 —	1.000
1961	0.024 (0.020)	1.024	0.024 (0.014)	1.025
1962	0.021 (0.023)	1.021	0.028 (0.016)	1.029
1963	0.033 (0.028)	1.034	0.044 (0.020)	1.045
1964	0.029 (0.034)	1.029	0.059 (0.024)	1.061
1965	0.077 (0.041)	1.080	0.071 (0.029)	1.074
1966	0	1.000	0	1.000

Table 8.3 (*continued*)

	Price Index				
	Chevrolet		Ford		
Year	$\log \bar{p}_t$	$\bar{p}_t$	$\log \bar{p}_t$	$\bar{p}_t$	Ratio
1961	7.420 (0.025)	$1670	7.385 (0.017)	$1612	0.966
1962	7.395 (0.022)	1627	7.372 (0.016)	1590	0.978
1963	7.331 (0.023)	1527	7.349 (0.016)	1554	1.020
1964	7.379 (0.026)	1602	7.382 (0.018)	1607	1.003
1965	7.392 (0.031)	1623	7.371 (0.021)	1589	0.979
1966	7.385 (0.036)	1611	7.392 (0.025)	1623	1.007
1967	7.362 (0.036)	1575	7.378 (0.025)	1600	1.016

	Depreciation index			
	Chevrolet		Ford	
Age	$\log D_\tau$	D_τ	$\log D_\tau$	D_τ
1	0 —	1.000	0 —	1.000
2	−0.167 (0.020)	0.846	−0.175 (0.014)	0.839
3	−0.317 (0.022)	0.729	−0.339 (0.015)	0.712
4	−0.470 (0.026)	0.625	−0.499 (0.018)	0.607
5	−0.651 (0.031)	0.521	−0.680 (0.022)	0.507
6	−0.854 (0.038)	0.426	−0.877 (0.026)	0.416

Table 8.3 (*continued*)

Summary statistics		
	Chevrolet	Ford
Standard error	0.036	0.025
Sum of squared residuals	0.02576	0.01256
R^2	0.995	0.998

its quality relative to that of the 1966 Chevrolet. Thus the arbitrary normalization for Chevrolet carries over to Ford, in the sense that only the trend of quality change of Fords relative to the trend in Chevrolets can be estimated. The overall trend remains unmeasurable.

A second hypothesis of interest on the relation between Chevrolets and Fords is that they have the same depreciation index. There is no strong economic reason to believe that this is true, but it is worth investigating for the purpose of economizing on parameters.

The two hypotheses just mentioned are linear restrictions on the parameters of the master model presented in Table 3.3. We consider the following two F-statistics: (1) for testing the hypothesis of perfect substitutability against the master model, and (2) for testing the hypothesis of equal depreciation indexes against the master model restricted to perfect substitutability. If Q_0 is the sum of squared residuals for the master model, Q_1 is the sum of squared residuals for the regression with only the constraint of perfect substitutability imposed, and Q_2 is the sum of squared residuals with both constraints imposed, then the statistics are $\frac{1}{5}(Q_1 - Q_0)/\frac{1}{40}Q_0$ and $\frac{1}{5}(Q_2 - Q_1)/\frac{1}{45}Q_1$. If in fact both constraints are true, these statistics both are distributed as F. Further, it is known that they are independent (Hogg 1961). This establishes a rigorous basis for separate tests of the two hypotheses.

The F-statistic for the hypothesis of perfect substitutability against the master model with no constraints across makes is 0.68 with 5 and 40 degrees of freedom. The corresponding critical F at the 0.05 level is 2.45. We conclude that there is no strong evidence against perfect substitutability, and, since there are reasonably persuasive economic arguments in its favor, we proceed by imposing the constraint in the remainder of this work.

The value of the F-statistic for the hypothesis of identical depreciation functions is 0.18 with 5 and 45 degrees of freedom; the critical F at the 0.05 level is 2.43. This suggests that it is not unreasonable to impose the

Table 8.4. Regression Results for Unrestricted Quality Change and Perfect Substitutability between Makes

Vintage	Index of quality: Chevrolet $\log b_v$	Chevrolet b_v	Ford $\log b_v$	Ford b_v	Price index (constrained equal for both makes): Year	$\log \bar{p}_t$	$\bar{p}_t$	Depreciation index (constrained equal for both makes): Age	$\log D_\tau$	D_τ	Summary statistics	
1955	−0.354 (0.047)	0.702	−0.305 (0.047)	0.737	1961	7.416 (0.017)	$1663	1	0.000 —	1.000	Standard error	0.029
1956	−0.237 (0.037)	0.789	−0.275 (0.037)	0.760	1962	7.393 (0.015)	1625	2	−0.168 (0.012)	0.846	Sum of squared residuals	0.04351
1957	−0.190 (0.030)	0.827	−0.185 (0.030)	0.832	1963	7.346 (0.016)	1550	3	−0.321 (0.015)	0.726	R^2	0.996
1958	−0.180 (0.024)	0.836	−0.144 (0.024)	0.866	1964	7.384 (0.019)	1609	4	−0.474 (0.019)	0.623		
1959	−0.100 (0.020)	0.905	−0.096 (0.020)	0.909	1965	7.381 (0.023)	1605	5	−0.651 (0.024)	0.522		
1960	0 —	1.000	−0.027 (0.017)	0.973	1966	7.384 (0.027)	1610	6	−0.848 (0.029)	0.428		
1961	0.023 (0.017)	1.023	0.005 (0.017)	1.005	1967	7.362 (0.030)	1575					
1962	0.021 (0.019)	1.022	0.015 (0.019)	1.015								
1963	0.037 (0.023)	1.038	0.034 (0.023)	1.035								
1964	0.035 (0.027)	1.035	0.055 (0.027)	1.056								
1965	0.078 (0.033)	1.081	0.079 (0.033)	1.082								
1966	0 —	1.000	0.016 (0.042)	1.016								

constraint, especially since the rather good fit of these regressions makes the test quite powerful.

The regression results for the model with both constraints are presented in Table 8.4. The quality coefficients for Chevrolet are essentially unchanged from their values in Table 3.3. The quality coefficients for Ford are also essentially unchanged, except they are renormalized to have a steeper trend. The arbitrary normalization used in the previous regression is replaced by the normalization, deduced from the data, that the 1960 Ford was 2.7-percent less efficient than the Chevrolet of the same year, but that the 1966 Ford was 1.6-percent more efficient than the 1966 Chevrolet. In other words, the trend in the relative price observed in Table 8.3 can be explained as an improper normalization for Ford. If, on the other hand, there had been substantial variations in the relative prices in Table 8.3 that could not be explained by renormalizing the Ford quality coefficients, then the null hypothesis of perfect substitutability would have been rejected.

The quality coefficients in Table 8.4 have been brought fairly close to each other by the renormalization, suggesting that it might be interesting to test the hypothesis that they are, in fact, the same. The F-statistic for this restriction on the results of Table 8.4 is 0.90 with 12 and 50 degrees of freedom, compared to the critical point of 1.96 at the 0.05 level. There is no strong evidence against this hypothesis, which amounts to holding that Chevrolets and Fords are identical in every respect. On the other hand, there is no convincing reason to believe that it is true, and it has the disadvantage that it is inconsistent with the hypothesis to be investigated in the next section.

The logs of the depreciation coefficients in Table 8.4 lie quite close to a straight line. They would lie exactly on it if depreciation were of the geometric or declining balance form. Since this form of depreciation corresponds to geometric deterioration or radioactive decay of capital, and that model of deterioration has such an important role in empirical capital measurement and in capital theory, it is of some interest to test the geometric restriction against the more general model of Table 8.4.[11] The constrained regression gives a rate of depreciation (or deterioration) of 0.1653 with standard error 0.0062, very close to the value implicit in the results of Table 8.4. Nonetheless, the null hypothesis is rejected; the F-statistic is 3.59 with 4 and 50 degrees of freedom, compared to a critical F at the 0.05 level of 2.57. Again, this test has quite high power; the proper

11. This is the only interesting null hypothesis about the deterioration function that can be stated as a linear restriction on the depreciation function.

interpretation of rejection of the geometric hypothesis is that while depreciation is almost certainly not geometric, the geometric function is probably a reasonable approximation for many purposes. Certainly, there are no grounds for believing that any very serious error has been committed by using a geometric deterioration function in calculating capital stock. On the other hand, the regressions of the present study should properly contain the unrestricted depreciation variables.

4. Estimates of Quality Change under the Assumption That It Is a Function of the Characteristics of Capital Goods: A Modified Hedonic Method

So far we have dealt with quality change as if it were a mystery to be measured but not explained. Except for the inability of our method to measure the overall exponential trend in quality change, its application to measuring the efficiency of pickup trucks has been relatively successful. Nevertheless, the trend is the single most interesting part of the quality index and of the quality-corrected price index, and it would leave things in rather an unsatisfactory state for it to remain unmeasured.

The measurement of the exponential trend in embodied technical change requires the development of a framework of capital measurement in which the notion has an unambiguous definition. As we have seen, if our framework is restricted to consideration of the *efficiency* of capital in use, the trend is ambiguous, and it would be senseless to try to estimate it. An alternative to this view is to suppose that embodied technical change, far from being a mystery, can be explained in terms of changes in the observed *characteristics* of capital goods. By characteristics we mean size, weight, power, and other information of an engineering nature. This hypothesis might be formulated as

$$b_v = H(x_{v1}, \ldots, x_{vM}), \tag{4.1}$$

where $x_{v1}, \ldots, x_{vM}$ are the values of M variables measuring the characteristics of the capital good of vintage v.[12] This view can immediately remove the ambiguity in the definition of the trend in embodied technical change. When only the efficiency of capital in use was considered, an upward trend in efficiency could be attributed equally well to a trend in the efficiency of the use of capital goods (disembodied technical change) or

12. The depreciation index may also depend on the characteristics, but this possibility is not considered in the present paper.

to a trend in the efficiency of capital itself. Any restriction on the b_v index that reduces its dimensionality by 1 eliminates this one-parameter ambiguity. As long as the number of unknown parameters in H is less than $T + N - 2$, the hypothesis of equation (4.1) is likely to eliminate the ambiguity.

The mere statement that a functional relation exists between a set of characteristics and the quality index may be enough to make it possible to estimate the trend in quality. If all of the characteristics are the same for two different vintages, then the existence of the functional relation requires that the quality index be the same for those two vintages. This fact can be used to replace the arbitrary normalization with a factual one and to identify the trend in embodied technical change.

Suppose it were known that two successive vintages had exactly the same embodied efficiency. Then the dummies for the separate vintages could be collapsed into a single variable with the value 1 for both vintages. The usefulness of this procedure lies in the fact that it would then be possible to add the dummy variable for vintage T that was previously outlawed. The hedonic information that two vintages have the same efficiency embodied in them is exactly a normalization of the kind needed to estimate an index of embodied technical change or quality for all vintages. The significant advance is that it is no longer an *arbitrary* normalization, so the resulting estimates include the exponential trend of quality change as well as departures from it. This method is properly attributed to Phillip Cagan, since he introduced it in a somewhat different framework in an important paper on the measurement of quality change from the prices of used automobiles (1965). Briefly, Cagan's method is the following. Under the assumption of geometric depreciation, it is possible to estimate the rate of depreciation from the ratios of the prices of two successive vintages known to have the same quality coefficient. For example, if the 1958 and 1959 models are the same, then $1 - \delta$ can be estimated as the average of the ratio of the price of the 1958 model to the price of the 1959 model in 1960, 1961, and subsequent years. Then the ratios between the quality coefficients of successive vintages can be estimated as the averages of the ratios of the prices of the models in the secondhand market, corrected for depreciation as calculated previously.

Two objections to Cagan's procedure can be raised. First, it is not explicitly econometric; that is, it does not attempt to calculate statistically optimal estimates starting from an assumption about the nature of the random disturbances. This is a relatively minor shortcoming, but it does mean that there is no indication of the reliability of Cagan's estimates. The econometric method mentioned earlier in this section could be used to carry out an econometric version of Cagan's method; it does not seem likely that the results could be very different from the application of his original method.[13]

Cagan himself raises a much more fundamental objection to his method: It is sensitive in the extreme to errors in the choice of identical vintages. Any departure of the actual rate of growth in efficiency from vintage v^* to vintage $v^* + 1$ from its assumed value of zero is automatically manifested as an error of the same magnitude in the rate of growth of efficiency in every vintage. The result is that the overall trend in efficiency is estimated with great unreliability, although, once again, relatively accurate estimates of departures from the trend can be obtained.

Since information on the characteristics of capital seems to provide the most likely approach to identifying the trend in quality change, either by something like Cagan's method or by parametrizing the function H, it is useful to examine the data at hand on the characteristics of pickup trucks. In Table 8.5 we present data on seven characteristics published in the *Used Car Guide*. The first two characteristics, wheelbase and shipping weight, are general indicators of change from one model to the next. The next four characteristics refer specifically to the engine. The first of these, displacement, changes only when a completely redesigned engine block is introduced—there were only two such changes for Chevrolet and one for Ford in the entire period. The second engine characteristic, the ratio of bore to stroke, measures the modernity of the engine design; in only one year did it decrease, and that was for the 1966 Chevrolet, which does rather badly no matter what specification is used. The rated horsepower and torque are also given; these change much more frequently than the characteristics of block design. The final characteristic is tire width.

A variant of Cagan's method is suggested by these data on characteristics. For both makes, there are at least two pairs of vintages that are apparently identical. Putting two constraints on the quality index for each make will go far to meet the second objection to Cagan's method. The constraints chosen are $b_{1956} = b_{1957}$ and $b_{1961} = b_{1962}$ for Chevrolet, and $b_{1957} = b_{1958}$ and $b_{1962} = b_{1963}$ for Ford. Relative to the model of Table 8.4, this involves one substantive constraint on the Chevrolet quality index (one of the constraints replaces the arbitrary normalization) and two on the Ford quality index. The data of Table 8.5 suggest additional constraints for both makes, but it is perhaps most interesting to

13. Actually, no new regressions would have to be run to do this. The results of section 3 could simply be renormalized so that $b_{v^*} = b_{v^*+1}$ instead of $b_T = 1$, where v^* and $v^* + 1$ are vintages known to have the same quality coefficient.

Table 8.5. Characteristics of Half-ton Pickup Trucks

Year	L	W	D	B	H	Q	T
				Chevrolet			
1955	115	3137	233.5	0.905	118	204	6.00
1956	114	3217	233.5	0.905	140	210	6.70
1957	114	3217	233.5	0.905	140	210	6.70
1958	114	3273	233.5	0.905	145	215	6.70
1959	114	3260	233.5	0.905	135	217	6.70
1960	114	3395	233.5	0.905	135	217	6.70
1961	114	3390	233.5	0.905	135	217	6.70
1962	114	3385	233.5	0.905	135	217	6.70
1963	114	3190	230.0	1.192	125	210	6.70
1964	114	3175	230.0	1.192	125	210	6.70
1965	114	3190	230.0	1.192	140	220	7.75
1966	115	3195	250.0	1.096	155	235	7.75
				Ford			
1955	110	3080	223	1.008	118	195	6.00
1956	110	3070	223	1.008	133	202	6.70
1957	110	3110	223	1.008	139	207	6.70
1958	110	3110	223	1.008	139	207	6.70
1959	110	3098	223	1.008	139	207	6.70
1960	110	3105	223	1.008	139	203	6.70
1961	114	3129	223	1.008	135	200	6.70
1962	114	3244	223	1.008	135	200	6.70
1963	114	3254	223	1.008	135	200	6.70
1964	114	3220	223	1.008	135	200	6.70
1965	115	3170	240	1.257	150	234	7.75
1966	115	3260	240	1.257	150	234	7.75

L = Wheelbase, inches.
W = Shipping weight, pounds.
D = Displacement, cubic inches.
B = Ratio of bore to stroke.
H = Horsepower.
Q = Torque, pound-feet.
T = Tire width, inches.

look at results for a small number of constraints. These results are presented in Table 8.6. The quality indexes for both makes are similar to those in Table 8.4, except that the upward trend is much less pronounced,

Table 8.6. Regression Results with Constrained Quality Index for Apparently Identical Vintages

	Index of quality				Price Index (constrained equal for both makes)			Depreciation Index (constrained equal for both makes)			Summary statistics	
Vintage	$\log b_v$	b_v	$\log b_v$	b_v	Year	$\log \bar{p}_t$	$\bar{p}_t$	Age	$\log D_\tau$	D_τ		
1955	−0.250	0.779	−0.202	0.818	1961	7.415	$1661	1	0.000	1.000	Standard error	0.029
	(0.063)		(0.063)			(0.017)			—		Sum of squared	
1956			- 0.192	0.826	1962	7.413	1658	2	−1.188	0.829	residuals	0.04636
1956–1957	−0.138	0.871	(0.049)			(0.020)			(0.016)		R^2	0.996
	(0.040)											
1957					1963	7.388	1616	3	−0.361	0.697		
1957–1958			0.111	0.895		(0.027)			(0.025)			
			(0.031)									
1958	−0.139	0.870			1964	7.446	1712	4	−0.535	0.586		
	(0.029)					(0.035)			(0.035)			
1959	−0.080	0.923	−0.075	0.928	1965	7.463	1742	5	−0.734	0.480		
	(0.021)		(0.021)			(0.046)			(0.044)			
1960	0.000	1.000	−0.027	0.973	1966	7.486	1784	6	−0.950	0.387		
	—		(0.017)			(0.056)			(0.054)			
1961			−0.016	0.985	1967	7.485	1781					
1961–1962	−0.008	0.992	(0.020)			(0.067)						
	(0.022)											
1962												
1962–1963			−0.027	0.974								
			(0.030)									
1963	−0.025	0.975										
	(0.037)											
1964	−0.048	0.954	−0.027	0.973								
	(0.048)		(0.048)									
1965	−0.024	0.976	−0.023	0.977								
	(0.059)		(0.059)									
1966	−0.123	0.884	−0.107	0.898								
	(0.073)		(0.073)									

and in fact disappears after 1960. As suggested in Section 3, the arbitrary normalization used in the earlier regressions appears to have *overstated* the true trend in quality change, if the present results are to be trusted. As a consequence of the much lower rate of quality improvement (essentially zero for the 1960–1965 models), the quality-corrected price index in the second part of Table 8.6 shows evidence of a positive true rate of inflation.

Since the present regression is a constrained version of the regression of Table 8.4, it is possible to carry out a formal test of the hypothesis that the apparently identical vintages have the same quality coefficients. The F-statistic for this test is 1.09 with 3 and 50 degrees of freedom, compared to the critical F at the 0.05 level of 2.80. There is thus no strong evidence against the hypothesis.

If we are willing to make stronger assumptions about the function H, then estimates of the quality coefficients can be obtained that are substantially better than those just presented, provided the assumptions are true. This requires a departure from the nonparametric character of the earlier parts of this study. Thus our remaining discussion of estimation under the "hedonic"[14] view of embodied technical change is carried out under the assumption that a log-linear functional form is a satisfactory approximation to the function, H. Since b_v is still an index, we need to restrict the elasticities, say, $\alpha_1, \ldots, \alpha_M$ to values that guarantee that $b_1 = 1$. This can be done by measuring all of the x-variables as ratios to their base-year values:

$$\hat{x}_{vj} = x_{vj}/x_{1j}, \qquad j = 1, \ldots, M. \tag{4.2}$$

The H-function obtained is

$$\log b_v = \alpha_1 \log \hat{x}_{v1} + \cdots + \alpha_M \log \hat{x}_{vM}. \tag{4.3}$$

Our previous unrestricted specification of Section 3 is a special case of this one, in which each x-variable is a dummy variable having the value 1 for one vintage and the value 0 for all other vintages. For Chevrolet, there is one dummy variable for each vintage except vintage 1 and vintage T, or $M = N + T - 3$ in all. In the regression of Table 8.6, two of the dummies have the value 1 for two successive vintages, for both Chevrolet and Ford.

Now we proceed to a consideration of the full hedonic specification, in which engineering variables (rather than dummy variables) appear in the expression for b_v. Both Cagan and Griliches (in his survey of hedonic methods, 1967) refer to Cagan's method as an alternative or supplement to the ordinary hedonic method. Our proposal is essentially to combine the two approaches in a single econometric equation. Note that this requires a slight formal modification of the traditional hedonic view, since that view relates the characteristics of a capital good directly to the price of the capital good when new. In our view, characteristics determine the efficiency of capital goods, and the present value of future efficiency determines the prices of new and used capital goods.

Although most of our right-hand variables are engineering measurements in our full hedonic method, it should be recognized that many of them serve as dummy variables as well. Our interest is directed more toward the derived estimates of b_v than toward the regression coefficients $\alpha_1, \ldots, \alpha_M$. If, as seems inevitable, some important characteristics are omitted from our x-variables, the α-coefficients may be seriously biased, but as long as some of the included variables are highly correlated with the omitted ones, the estimates of b_v may be fairly close to the truth. Since engineering changes frequently occur together, there is reason to hope that the omitted variables are fairly highly correlated with the included ones.

Our method may be viewed as a substantial generalization of Cagan's method. Instead of taking a single pair of vintages and constraining their embodied efficiences to be equal, the embodied efficiences of *every* pair of vintages with similar characteristics are constrained to be equal. This fact alone makes the method significantly less arbitrary than Cagan's. Furthermore, we make the not unreasonable assumption that the contribution to efficiency of each characteristic is proportional to the departure of the characteristic from its base year value. This constrains the estimated efficiencies in years with only small changes in the characteristics to be close together. This feature is entirely absent from Cagan's method. The consequence of the imposition of these constraints is to reduce the number of right-hand variables from the number of vintages to the number of characteristics, with a corresponding improvement in the quality of the estimates, provided the constraints are true.

Experimentation with a variety of hedonic specifications indicated that it was probably useful to include three dummy variables in the regressions in addition to the variables measuring characteristics. These were (1) a dummy variable with value zero for Chevrolet and 1 for Ford, to measure any constant difference in quality between the two makes; (2) a dummy variable for the 1955 Chevrolet, because of a mid-year model change, and (3) a dummy variable for the 1966 Ford, because of a change in the front suspension that is not covered by the measured characteristics.

14. "Hedonic" is hardly the right term in dealing with ordinary pickup trucks, but its use is suggested by the related body of literature on automobiles.

Table 8.7. Regression Results for the Hedonic Specification

Price index (constrained equal for both makes)			Coefficients of characteristics			Depreciation index (constrained equal for both makes)			Summary statistics	
Year	log $\bar{p}_t$	$\bar{p}_t$	Characteristic	Chevrolet	Ford	Age	log D_τ	D_τ		
1961	7.410 (0.015)	$1652	Wheelbase	—	2.25 (0.77)	1	0.000 —	1.000	Standard error	0.0292
1962	7.410 (0.013)	1653	Weight	1.82 (0.41)	−0.51 (0.46)	2	−0.189 (0.013)	0.828	Sum of squared residuals	0.04959
1963	7.387 (0.014)	1615	Ratio of bore to stroke	0.01 (0.17)	2.40 (0.66)	3	−0.366 (0.015)	0.693	R^2	0.995
1964	7.450 (0.016)	1720	Horsepower	−0.88 (0.25)	3.95 (0.75)	4	−0.542 (0.018)	0.581		
1965	7.470 (0.019)	1754	Torque	−0.20 (0.52)	−3.26 (0.88)	5	−0.745 (0.022)	0.475		
1966	7.495 (0.024)	1798	Tire width	0.77 (0.32)	−3.19 (0.84)	6	−0.964 (0.027)	0.381		
1967	7.495 (0.028)	1799	1955 dummy	−0.13 (0.05)	—					
			1966 dummy	—	−0.07 (0.04)					
			Ford dummy	—	−0.022 (0.015)					

Further, the displacement variable was excluded for both makes; its coefficient was essentially zero for Chevrolet and the variable was linearly dependent on the other characteristics for Ford.

Results for the hedonic specification are given in Table 8.7. The quality-corrected price index presented in the first part agrees quite closely with the index in Table 8.6, except that it is slightly (but not significantly) more inflationary than the earlier results. There is a compensating increase in the rate of depreciation, as can be seen by comparing the third parts of the two tables.

The coefficients of the characteristics and vintage dummy variables are given in the second part of Table 8.7. These can be interpreted as the elasticities of quality with respect to the various characteristics. Two disturbing features of these estimates are immediately apparent. First, many of the coefficients are surprisingly large, especially in the case of Ford. Second, there is complete disagreement between the coefficient for the same characteristic for Chevrolet and Ford. The latter is completely inconsistent with the basic hypothesis of previous hedonic work, in which the contribution of characteristics has been measured in a cross section of different makes. The hypothesis that the hedonic coefficients are actually the same is emphatically rejected in the results of Table 8.7. The F-statistic is 13.69 with 5 and 58 degrees of freedom, compared to a critical F of 2.38 at the 0.05 level. This seems to be strong evidence that the measured characteristics are seriously incomplete and are serving as dummy variables for important changes in unmeasured characteristics.

The quality index implicit in the hedonic regression can be calculated by applying the coefficients to the matrix of characteristics. In addition, the standard errors of the quality coefficients can be calculated by the usual method for the sampling properties of a linear combination of regression coefficients. These are presented in Table 8.8. The quality indexes for both makes are quite similar, except that, as mentioned earlier, the rate of quality change here is slightly lower than in the indexes in Table 8.6. The standard errors are substantially smaller for the hedonic indexes than for the earlier ones, exactly because additional information in the form of the hedonic constraints is used in the hedonic indexes.

The hedonic model is to a very close approximation a constrained version of the model of Table 8.6. The approximation arises because the weight of the Chevrolet dropped by 5 pounds between 1961 and 1962, and that of the Ford increased by 10 pounds between 1962 and 1963. In both cases the small change was ignored in the earlier results, but appears in the results of Table 8.8. The latter coefficients fail to meet the constraint of the earlier model by 0.002 in both cases, presumably an amount small

Table 8.8. Quality Index Calculated from Hedonic Regression Results

	Chevrolet		Ford	
Vintage	log b_v	b_v	log b_v	b_v
1955	−0.231	0.794	−0.182	0.834
	(0.043)	0.794	(0.043)	
1956	−0.124	0.884	−0.175	0.840
	(0.026)		(0.033)	
1957	−0.124	0.884	−0.087	0.917
	(0.026)		(0.017)	
1958	−0.128	0.880	−0.087	0.917
	(0.019)		(0.017)	
1959	−0.074	0.929	−0.085	0.919
	(0.017)		(0.018)	
1960	—	1.000	−0.022	0.978
	—		(0.015)	
1961	−0.003	0.997	−0.013	0.987
	(0.001)		(0.014)	
1962	−0.005	0.995	−0.031	0.969
	(0.001)		(0.014)	
1963	−0.036	0.965	−0.033	0.968
	(0.018)		(0.015)	
1964	−0.045	0.956	−0.027	0.973
	(0.018)		(0.013)	
1965	−0.033	0.968	−0.032	0.969
	(0.030)		(0.030)	
1966	−0.134	0.875	−0.117	0.889
	(0.037)		(0.040)	

enough to ignore. The approximate F-statistic for testing the hedonic constraint (exact except for the difficulty just mentioned) is 0.74, with 5 and 53 degrees of freedom, compared to the critical F of 2.40 at the 0.05 level.

5. The Uses of Secondhand Market Data in Price Measurement

The results of the previous two sections are sufficiently encouraging to suggest that secondhand market data are potentially a rich source for price measurement. We have demonstrated, implicitly, two uses of these

data. First, the relative qualities of different vintages can be inferred from their relative prices, except that identification of the trend in quality change requires the use of additional information. The hedonic method of Section 4 was a not entirely successful attempt at this. Second, a price index can be calculated as a suitably adjusted average of the prices of all of the vintages observed in each year. The adjustments required for price measurement are for both quality change and depreciation. Even if the price index sought is not to be corrected for quality change, it is essential to take account of quality change in calculating it. We will give an example of the need for this below. Both of these uses of secondhand data appear implicitly in our regressions; the distinction between them is logical rather than practical.

To compare the results of our calculations with those based on other methods, we present in Table 8.9 a set of price indexes for pickup trucks

Table 8.9. Various Price Indexes

Year	Pickup trucks, quality-corrected, this study[a] (1)	Ford pickup trucks, index of (1) without quality correction[b] (2)	Ford pickup trucks, no allowance for quality change, this study[c] (3)	WPI, motor trucks[d] (4)	CPI, new cars[e] (5)	CPI, used cars[f] (6)	List price, Fords[g] (7)
1961	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1962	1.001	0.983	1.032	0.998	0.996	1.141	1.007
1963	0.978	0.959	1.051	0.989	0.986	1.190	1.018
1964	1.041	1.026	1.121	0.985	0.992	1.238	0.999
1965	1.062	1.043	1.139	0.995	0.947	1.289	1.000
1966	1.088	0.980	1.189	0.998	0.945	1.212	1.052
1967	1.089	—	1.173	1.014	0.946	1.217	1.118

[a] $\bar{p}_t$ from Table 8.7, converted to index
[b] $\bar{p}_t b_t$ for Ford from Tables 8.7 and 8.8, converted to index
[c] $\bar{p}_t$ for Ford from Table 8.2, converted to index
[d] Wholesale Price Index, motor truck component, Bureau of Labor Statistics (April of given year)
[e] Consumer Price Index, new car component, BLS (March of given year)
[f] Consumer Price Index, used car component, BLS (March of given year)
[g] Advertised delivered price, Ford pickup, *Used Car Guide.*

and related capital goods. The first column is the set of price estimates, $\bar{p}_t$, from Table 8.7, reduced to an index based in 1961. The second column gives the price per new truck estimated from the same regression; it is calculated as the price per unit of efficiency, $\bar{p}_t$, multiplied by the efficiency of a new truck, b_t. This is the price index not corrected for quality, mentioned above. The third column is the set of $\bar{p}_t$ coefficients from Table 8.2, reduced to an index. This index is not only not corrected for quality change, but the existence of quality change was ignored in calculating it. The fourth column gives the Wholesale Price Index for motor trucks, the most detailed index available from the Bureau of Labor Statistics for pickup trucks. The fifth column is the well-know Consumer Price Index for new automobiles, incorporating significant corrections for quality change; the sixth column is the used car price index from the same source. Finally, the seventh column is an index of the list price of new Ford pickup trucks.

The quality-corrected price index from the present study, column 1, shows inflation beginning in 1964, while the list price index (column 7) is stable until 1966, and the WPI is stable through 1967 (it moves upward sharply in 1968). Under our basic hypothesis of perfect substitutability between new and used trucks, column 1 can be interpreted as an index of the actual transaction price for new trucks. Thus, if the hypothesis is even approximately correct, the comparison of our index with either the list price index or the WPI suggests a substantial reduction in the difference between list and transaction prices for the early years of the recent economic expansion. The Wholesale Price Index behaves more like the list price index than like our estimate of the actual price. If our results were assumed to be representative of all durable goods, a significant reinterpretation of the aggregate pattern of inflation since 1964 would be in order, since the current evidence is derived from the WPI. No such claim is made here, however.

In spite of the fact that pickup trucks and automobiles are probably fairly close substitutes in production, there is no observable connection between the quality-corrected index for pickups in column 1 and the quality-corrected index for automobiles from the CPI in column 5. The CPI does not show any response at all to the inflationary pressure of the years after 1963. Furthermore, it has a slight downward trend of just under 1 percent per year, while our index rises at a rate of over 1 percent per year. Either automobiles are becoming 2-percent per year less expensive to produce than pickup trucks, or the quality corrections in one or both indexes are systematically biased. Again, no strong claims in favor of the method of this study are sustained by the evidence.

Finally, we note that the index calculated from Table 8.2 (column 3) and the CPI for used automobiles behave in very much the same way. The first index is essentially an average over all surviving vintages of prices in the secondhand market, adjusted for depreciation but not for differences in quality. The CPI is probably calculated in much the same way. Both appear to suffer from the same error: Quality improved rapidly in the late fifties and remained roughly constant in the early sixties, for both pickups and automobiles (on the latter, see Triplett 1966). In each succeeding year in the sixties, a price observation for a low-quality vintage of the fifties is dropped from the calculation of the average price over vintages, and a sixties-quality observation is added. The result is a false inflationary bias as long as low-quality vintages are being dropped. This can be seen in both columns 3 and 6—they rise sharply during the noninflationary years 1961–1964, and then remain roughly constant after 1964. The appropriate way to calculate a price index without quality correction from secondhand price data is to adjust each vintage price for its quality relative to the quality of the current new unit. This is the method used in calculating column 2, which is substantially different from (and more reasonable than) the index of column 3, although it is derived from the same data.