Volume Title: The Economics of New Goods

Volume Author/Editor: Timothy F. Bresnahan and Robert J. Gordon, editors

Volume Publisher: University of Chicago Press

Volume ISBN: 0-226-07415-3

Volume URL: http://www.nber.org/books/bres96-1

Publication Date: January 1996

Chapter Title: Quality-Adjusted Prices for the American Automobile Industry: 1906-1940

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Chapter URL: http://www.nber.org/chapters/c6065

Chapter pages in book: (p. 71 - 108)

2 Quality-Adjusted Prices for the American Automobile Industry: 1906–1940

Daniel M. G. Raff and Manuel Trajtenberg

2.1 Introduction

The empirical literature on new goods has long shown an interest in the automobile. The hedonic approach was introduced to the profession in Court's 1939 attempt to measure the evolution of automobile prices on a quality-adjusted basis. Griliches (1961), Triplett (1969), Ohta and Griliches (1976), and Gordon (1990, chap. 8), all leading references, continued the study of the industry. Yet each of these, only Court excepted, is focused on developments that took place in the years after the Great Depression, a period when the automobile as an innovation was clearly mature. Recent research suggests that the largest contributions of new goods to welfare changes may well come much earlier on (Trajtenberg 1990). The industry's annual model changes pose the price index question perfectly well in the postwar period. But the most salient questions about new goods necessarily take us further back in time.

Straightforward facts about the history of automobile manufacturing in America support this view. In the first three decades of this century, the indus-

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The authors are grateful to Timothy Bresnahan, Geoffrey Carliner, Martin Feldstein, Robert Gordon, Zvi Griliches, Thomas Marx, Jeanne Pryce, and Morton Raff for encouragement and practical assistance; to Thomas De Fazio, Jack Triplett, and Daniel Whitney for technical discussions; and to librarians at the Boston Public Library, the Detroit Public Library, the Harvard Business School, the Massachusetts Institute of Technology, and, above all, the Motor Vehicle Manufacturers Association for kind access to their collections. Erik Chuang provided superb research assistance managing a complex data-entry process. Even amid a large group of able and devoted data enterers, Irving Birmingham cannot pass unremarked. Roxanne Jones-Toler and Scott Stern were Spartans at the pass. The authors had useful comments from audiences at the 1994 NBER Summer Institute. This research was supported by the National Bureau of Economic Research and the National Science Foundation. The usual disclaimer applies.

try went from scarcely existing, insofar as Census of Manufacturers enumerators were concerned, to being in terms of the value of products the largest industry in the economy.[1] Over the period we study in this paper, the most casual observer can recognize how much the product changed. Manufacturing methods evolved equally dramatically. So too did market prices. In 1906, for example, there were no new automobiles for sale at a price equal to or below the gross national product (GNP) per capita at the time of \$336 (U.S. Bureau of the Census 1976, series F2). In fact, the average price in our database for that year is nearly ten times that amount. By 1940, when our data end, a household with a year's GNP per capita to spend (\$754) had a choice of fifty-nine different models, and the average price of cars on the market that year was only about twice that sum.

The industry saw tremendous changes over this period as well. Indeed, contrasted with the tight oligopoly and dull performance of the post–World War II decades, the vibrancy of these early years is almost shocking. There was an early and well-organized attempt at cartelization that failed. Entry eventually proceeded at a breakneck pace. Attracted by the palpably vast opportunities, hundreds of new firms burst onto the scene every year, the total running to well in excess of a thousand. More than ten thousand distinct models were on offer at one time or another. Intense competition in price and quality persistently pushed price-performance ratios to new lows.

The consequences were far reaching. One advertising slogan early in the period ran "One day, one dollar; one year, one Ford." In the very beginning, automobiles were strictly playthings of the rich. But well before 1940, cars were routinely purchased by ordinary working households. The consequences of this for American economic life were themselves pervasive and profound. At the turn of the century, even private urban transportation was often powered by horses. Roads were often dusty when dry and all but impassable when wet. But by 1940, the internal combustion engine ruled the road. Road-construction techniques were recognizably modern. All-weather paved roads existed all over the nation. Bedroom suburbs and even places of work and trade were located in areas where trains and trolleys did not run. The automobile was a new good with important consequences.

There is a vast literature on the industry's history.[2] However, quite surprisingly, it contains no systematic quantitative analysis of the period in which most of the technical change happened. Price indexes would be a useful start. We proceed in steps. The first is simply to complement the existing hedonic literature by pushing the span of its automobile quality-adjusted price calculations backward to 1906, thus closing in on the birth of the industry and the product. These price indexes can be used for a variety of purposes. We propose a crude decomposition of the price change into product- and process-

1. By value-added, it ranked 5th out of 326 in 1929. Combining it with the Census's automotive bodies and parts industry brings that rank to 1st as well.

2. For a recent survey see Flink (1988). His bibliography is extensive.

innovation components, identifying constant-quality price change with manufacturing economies and quality change with design improvement. We also use our indexes for comparisons to hedonic price indexes for other industries at a comparably early stage of the product life cycle and for comparisons to hedonic price indexes for this industry in the later periods previously studied. In particular, we couple our results to those of Gordon's (1990) analogous exercise for the post–World War II period to consider the industry's history in the long view. Finally, we assess several possible sources of bias in our results.

The paper proceeds in six main parts. Section 2.2 is a technical introduction to the product. In section 2.3 we discuss the data. In section 2.4 we give preliminaries to the hedonic analysis and discuss the regressions. In section 2.5 we present the main results in terms of quality-adjusted price indexes and put them in the wider context. In section 2.6 we consider the seriousness of two potential sources of bias in the index numbers. Section 2.7 concludes the paper.

2.2 Cars: A Technical Overview

Automobiles are complex products, arguably the most complex consumer durable at the turn of the century as well as now. This basic fact permeates our approach to measurement and hence to gathering data. We thus begin by recognizing that any design for a self-propelled land vehicle must confront a series of interrelated engineering problems. Any particular design (i.e., any particular vehicle a consumer might buy) represents a particular set of solutions to these problems.

The generic problems are simply stated. The first task is to generate power from the fuel in a sustainable fashion. Gasoline, for example, can be mixed with air and exploded in a controlled way in a confined space.[3] If one wall of the space can move relative to the others, the kinetic energy of the explosion becomes linear motion. This can be converted into rotary motion to turn wheels, and the rotary motion will be smoother if the mixing and exploding go on in several sites in some staggered sequence. All the mechanical elements involved in creating and transforming the linear motions need to be kept lubricated and relatively cool.

Since the car is heavy, especially when loaded with passengers, there is substantial inertia to be overcome in starting forward motion. Connecting the rotating shaft to a device that gears up or down to various degrees the speed of rotation helps in accomplishing this.[4] It is convenient to allow the operator to

3. Getting the power generation started poses some problems distinct from those of continuing it. The design of the valves letting the gases into, and eventually out of, the space is also a subject in itself.

4. Early automobile engines had a fairly flat torque curve. As engines became more efficient—in the engineer's sense of generating more power per unit displacement—torque curves became more peaked. The more this was so, the more convenient it was to operate the engine at a relatively steady pace irrespective of the speed at which one wanted the wheels to turn.This too made multiple gears desirable. (Both the phenomenon and the solution will be familiar to bicycle riders.)

engage and disengage the entire gear mechanism from the engine from time to time. When this (clutch) mechanism is engaged, the rotary motion then needs to be transmitted to at least some subset of the wheels, and this in a fashion that allows the vehicle to turn.[5] There must also be a steering mechanism to guide the turns and a braking system to slow or stop the vehicle as required. A body, with seats and upholstery, is essential to make the car useful, and there must be some system between the chassis frame and the wheels to mediate between irregularities in the road's surface and irregularities in the ride. For this latter reason and others, it has also proved convenient to mount tires on the wheels.

This functional description of a car touches on all the main mechanical systems. They are many, and none is simple in itself. In choosing specific solutions to each of the individual problems, general strategies must be adopted (e.g., the gasoline engine rather than, say, the steam engine or the electric motor), as well as detailed specifications for each of them (e.g., the numbers of cylinders and their dimensions, the compression ratio, the operating temperature range, etc.). Overall performance will be sensitive to each solution and often also to the interactions between them.

The potential for such system interaction is elaborate. It is not merely true, for example, that the systems making up the engine must be well adapted to one another: elements of the design of the entire power train and chassis may also be implicated. It is unfortunately very difficult to capture these interactions in summary variables. We thus adopted the second-best procedure of identifying the most important systems (from both engineering and manufacturing perspectives) and seeking data on their attributes. Our data set comprises roughly forty attributes representing the state of the systems.

2.3 Data

Computing quality-adjusted price indexes, even using as undemanding a method as the hedonic, requires large amounts of very detailed data. One needs prices and detailed attribute information for virtually all the different models marketed in each period.[6] Studies such as this thus rest firmly on the breadth of their data.

The primary source of most information about the identities and systems of individual models that covers any wide range of models is the set of specification tables published in the contemporary trade press at the time of the annual

5. When the vehicle turns,the inner and outer wheels cover different distances. They therefore need to rotate at different rates.

6. The more demanding methods, sketched in n. 13 below, are potentially more illuminating—for example, they can be used both to quantify welfare gains and to delineate their timing. The problem is that they require quantity data, that is, information on the quantities sold of each individual model in each year. No such database exists as of this writing. It is possible that one could be put together and coupled to the price and attribute data of this study. But doing this would be a major research enterprise in itself and was utterly beyond the scope of this paper.

Table 2.1 **Manufacturers and Models**

Year	Manufacturers	Mechanical Models	Body Models
1906	≅90	≅100	≅200
1908	61	132	153
1910	224	424	1,006
1912	161	316	977
1914	140	259	871
1916	121	192	495
1918	122	172	681
1920	126	155	569
1922	122	156	780
1924	93	127	696
1926	61	104	603
1928	48	117	784
1930	45	104	874
1932	33	90	752
1934	30	72	420
1936	26	64	460
1938	22	54	387
1940	21	62	414

Notes: The number given here for body models is the number for which we have data on price, wheelbase, and displacement. The number of body models in the underlying database is larger since in some early years data on displacement was not consistently available. The number of observations used in the regressions is slightly smaller since the regressions used only observations that also had complete information on the relevant systems.

New York Auto Show.[7] The trade journals vary in the attributes they report.[8] The attributes reported in each source also change slowly over time. The information given about some attributes is not as revealing as it might be.[9] The tables are nonetheless very detailed and an extremely rich data source.

Each mechanically distinct variant identified in the tables could usually be purchased with any of several different bodies. We call these pairings body models and use them as our unit of observation. We were constrained (by time and finances) to enter body-model data only for alternate years and to go back no further than 1906.[10] Table 2.1 gives some basic descriptive statistics. We have a total of over 11,000 observations (i.e., of body models offered). The number rises sharply in the earliest years, more through entry than through model proliferation. It peaks in 1910 at 1,006. There is a second surge after

7. Kimes and Clark (1985) gives somewhat more comprehensive coverage in its descriptive prose and images but not in its attribute descriptions.

8. This may be sensitive to the balance between consumers, the retail and repair trade, and manufacturers and engineers in each periodical's readership.

9. For example, the tables may report manufacturer rather than design type. Or they may report design types, but in a way that blurs the distinction between minor and major variants. With sufficient background research, however, much of this can be rendered useful.

10. Subsequent to the completion of this paper, we were able to extend the data set back to 1901. We will exploit the new data in future work.

World War I and a third at the end of the 1920s, after which time the number declines considerably. There was a pronounced decline in the number of manufacturers over the whole period and substantial model proliferation in the 1930s.

	Manufacturers	Body Models per Manufacturer
1910–20 average	153	5.1
1920–30	90	7.6
1930–40	30	18.4

After some research, we concluded that the attributes reported by the periodicals *Automotive Industries* and *Motor* together generally spanned the information available. We thus drew the data on attributes and prices from these periodicals.[11] Coverage was then compared against the listings in Kimes and Clark (1985), apparently the most authoritative hobbyist source. Spot checks with other researchers and comparisons with industry histories and other such investigations covering this period, published and otherwise, have revealed no important or systematically unutilized information.[12] It is important to note that our data represent only firms operating above a certain minimal economic threshold, namely ones that were large enough to make advertising at the major annual trade show attractive. We may thus have left out experimentalists and bespoke manufacturers so aloof from commerce that they left customers to find their own way to the factory. We have surely left out some hopeful entrepreneurs who had and possibly even announced bold plans but never in fact made any cars. But we have found no evidence that we have left out any products that were actually easy to buy, and this is the breadth of data that the hedonic method requires.

2.4 Hedonic Analysis: Preliminaries

The main goal of this paper is to construct price indexes that reflect as accurately as possible the vast improvements that took place in the design, manufacturing, and performance of cars during our chosen period. Given the fact that quantity data are unavailable, the only viable approach is to estimate hedonic price regressions and compute on that basis quality-adjusted price indexes. This has been the standard practice for the problem of quality adjustment since Griliches (1961).[13]

11. Our procedure was to code data on the selected attributes from the most comprehensive source of auto show mechanical-attribute tables available to us at the time of initial coding. We then went to that source's body tables to create the fuller row space in the identifier, price, and body-type columns and then copied the mechanical-attribute data appropriately. We then went to the other periodical's tables and augmented as appropriate both the row space of individual manufacturers' body models and the column space of attributes we thought worth recording.

12. The most notable unpublished source is Griliches and Ryan (1971).

13. If we had possessed detailed quantity data, we would have estimated discrete-choice models of demand, retrieved from them the underlying parameters of a utility function (i.e., marginal utilities of the attributes of cars and of income), and computed with the help of these welfare-

The hedonic approach has well-known limitations.[14] The fact that the hedonic surface reflects neither utility nor supply but rather the tangency between the two restricts the extent to which hedonic-based price indexes can be thought to capture fully the effects of quality change. Hedonic methods are particularly ill suited to periods of sharp change in technology (as might be reflected in shifts in the distribution of brands in attribute space). Nevertheless, hedonic quality-adjusted price indexes for cars during the first half of this century can significantly improve our knowledge of the evolution of this industry during its early stages. Moreover, since similar indexes for the post–World War II period are available (e.g., Gordon 1990), we can put together a series of quality-adjusted prices almost a century long for one of the most important sectors of the economy.

In this section we examine first the evolution of automobile prices over time (the dependent variable). We then consider the selection of attributes, that is, our explanatory variables. Finally, we present and discuss the estimates of hedonic price regressions from which our index number calculations derive.

2.4.1 Evolution of Automobile Prices

Since we study a relatively long period, the choice between using product prices stated in current dollars or corrected for changes in the general price level may be an important one. During our period there were two major swings in the general price level, the short but sharp inflation that followed World War I and the more familiar deflation that occurred at the onset of the Great Depression. Prices in the post–World War II period also had a complex history. Deflating raw prices by, for example, the Consumer Price Index (CPI) would control for this. Each series is illuminating in its own way. We present most of our results, here and later in the paper, in both ways.

Figure 2.1 shows the time series of mean prices in our data set, stated in current dollars. The most striking feature is the size of the drop. Automobile prices fell by 51 percent, from $3,290 in 1906 to $1,611 in 1940. The CPI rose during the same period by 59 percent and hence inflation-adjusted car prices dropped by almost 70 percent. To give a better sense of what these numbers mean, figure 2.2 translates them into terms more meaningful to us: in 1993 prices the average car offered in the 1906 market sold for $52,640; whereas by 1940 the mean had dropped to $16,565 (not so far, incidentally, from the average nominal price of cars in 1993). This dramatic fall in prices is one of the single most important facts pertaining to the evolution of the automobile industry in its first half century, reflecting as it does both momentous technological advances and vast expansion of the market for automobiles.

As with most developments in the history of the automobile, the price de-

based price indexes. Trajtenberg (1990) and Pakes, Berry, and Levinsohn (1993) illustrate the method. Such procedures obviate most of the thorny problems that arise (see, e.g., section 2.6 below) when using the hedonic method.

14. For a more expansive treatment of these matters, see Trajtenberg (1990, 34–44).

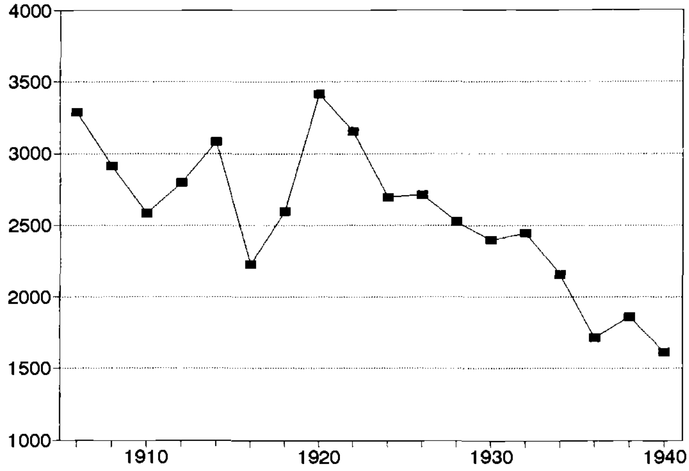

Fig. 2.1 Automobile prices 1906–1940 in current dollars

cline was far from uniform over time. The largest part of the fall in CPI-deflated prices occurred in two installments early in our period: from 1906 through 1910 and from 1914 through 1918. In the course of the latter four years, the CPI-deflated price of cars shrank by almost one-half (from over $44,000 to $25,000 in 1993 dollars).[15] From 1918 on there was for the most part a downward trend, but the overall drop was not nearly as dramatic as that of the earlier period.

The rise in prices from 1910 to 1914 was associated with a large and widespread increase in the size and power of cars. Why precisely the big 1914–18 decline occurred remains to be established. Recalling the dramatic introduction of mass-production methods at Ford at the end of calendar year 1913, it is tempting to attribute the subsequent sharp decline to Ford. Interpretive caution is in order here, however. Ford introduced mass production alone at first. There were very few different Ford models in those years. Ford cars therefore represent a tiny percentage of our sample. If we had weighted prices by sales in calculating the series, then the price drop would be much more dramatic, and a big part of it would be due to Ford. But our series was not generated in that way. It is possible that the course of the actual series owes to cross-price elasticities or to the discovery of new market niches. Tastes may also have shifted downward in time of war. There certainly was a noteworthy downsizing of cars on the market, but what the cause of this was we cannot yet say. The subsequent secular decline of the series presumably has something to do with

15. We see here, for example, how the information conveyed by looking at current prices is greatly distorted by the post–World War I inflationary surge. Nominal prices were actually higher in 1920 than in 1906, but controlling for inflation reveals that prices had dropped by more than one-half!

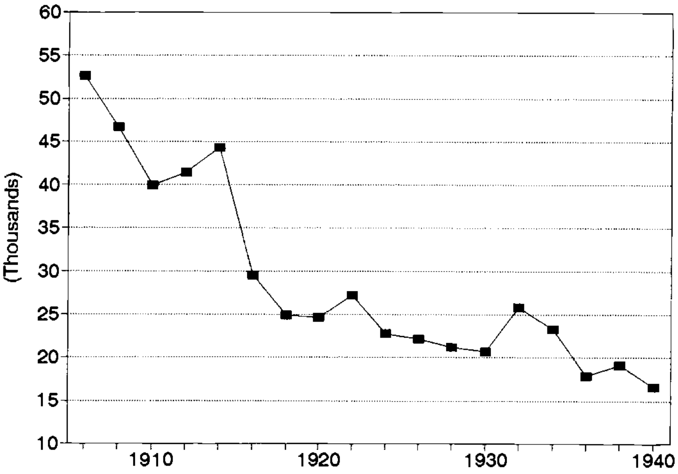

Fig. 2.2 Automobile prices 1906–1940 in constant 1993 dollars

the diffusion of mass-production methods across establishments, but that is a complex subject of its own (see Raff 1991 and Bresnahan and Raff 1991, 1993).

2.4.2 Selection of Attributes

One fundamental difficulty has beset all hedonic car studies from Court (1939) onward. It is that of identifying a set of attributes that can be taken to be the most important performance attributes of cars and that can be measured in a consistent fashion over time. Only if quality in this sense is quite tightly controlled for can we begin to regard as reliable quality-adjusted price indexes based on hedonic regressions.

Any quality-adjustment method requires regressors that would in principle go directly into a consumer's utility function. "Reliability," "smoothness of ride," "safety," "comfort," and so forth, are presumably the sort of attributes in question. But these are extremely hard to quantify in an objective or even consistent manner. Engineering (i.e., technical) attributes are much easier to measure, but they are certainly further removed from the quality dimensions perceived by consumers.

The difficulty in identifying structural relationships between engineering attributes and utility stems from the fact, sketched in section 2.2 above, that for all their pervasiveness and ease of operation, cars are extremely complex machines. Their overall performance depends in a complicated way upon the performance of each of their systems, upon trade-offs made between systems, and upon the extent to which their design is well integrated. All this makes it a formidable challenge to devise variables that will even proxy the performance of individual model designs in an unambiguous and parsimonious way.

We have made some progress in that respect in this study by including (apparently for the first time) actual measures for many of those systems (brakes, clutch, drive mechanism, etc.). Whether our selection of systems and variable definitions is the most appropriate or effective only further investigation will reveal.

In the end, we decided to include three categories of attributes in the hedonic regressions: measures of vehicle size, engine power, and the technology of five major engineering systems. Size and power have been used in virtually all automobile hedonics studies. They are very closely associated with price, and casual empiricism suggests that consumers do care about them. For systems, we initially attempted to cover all the major ones identified in section 2.2. In particular pairs of years, however, we often had to make significant compromises in the face of data limitations of various sorts.[16]

For size we use wheelbase, measured in inches.[17] For power we have available for most years two alternative measures: rated horsepower (HP) and displacement. We opt for the latter whenever it is available because it captures more information (i.e., stroke, bore, and number of cylinders).[18] The five systems we chose are the rear axle, clutch, brakes, drive type, and suspension. The dummy variables are defined in table 2.2 with their names as they appear in the hedonic regression results later in the paper.[19]

Each of these systems underwent dramatic changes over the period studied. Technical innovations, changes in demand, and the shifting interactions with related systems made particular designs emerge and diffuse, only to be superseded later by others. The methods of this project require us to trace and grasp the evolution of system design over time, both in order to define the categories that eventually appear as dummy variables in the hedonic regressions and to form priors as to the likely signs of their coefficients. In addition, we believe that the time paths followed by competing designs are of significant interest in themselves. They show vividly the contest between alternative systems and the speed of diffusion of those that emerged as dominant. We present in the appendix a technical and graphical description of the evolution of the main systems.

If one of the types should become a virtual standard (i.e., if its share among the competing models approaches 100 percent), then it approaches collinearity with the regressions' constant terms. The system can no longer be included in

16. Some systems that clearly are important did not exhibit sufficient variation (because a certain type was universally adopted very quickly). In other cases the qualitative categories reported in our sources were not consistent over time and hence could not be expressed across adjacent years as uniform dummy variables.

17. The results are very similar if one uses weight instead.

18. Rated HP is determined by a formula that is not sensitive to important features of engine design. In general, it is not the same as average or maximum HP. For the years 1906–10 we did not have consistent measures of displacement or its determinants and were obliged to use rated HP faute de mieux. We can observe that for the years for which we had both regressors, the results were not sensitive to which one we chose.

19. In the case of each dummy, of course, there is a residual category. Thus, for example, RAXLE50F = 1 if the rear axle was half floating, RAXLE50F = 0 if it was of a different type.

Table 2.2 Systems Variable Definitions

System	Variable
Rear Axle	RAXLEF: rear axle of the fully floating type
	RAXLE50F: rear axle of the half-floating type
Clutch	CLDISC: clutch using disc
	CLPLATE: clutch using plates
	CLSPLATE: clutch using a single plate
Brakes	BRIHYDRA: internal hydraulic brakes
Drive type	DRSBEVEL: drive, spiral bevel
	DRHYPOID: drive, hypoid
Suspension (spring type)	SPHELLIP: spring, half-elliptic

the regression. That is the case for the spring type from 1928 on, for example: the half-elliptical type had been adopted by then in over 95 percent of all cars marketed. In other cases, though, one type became dominant but then differentiated as subvariants appeared. In this case, the system can still be included: it merely requires a different dummy variable. For example, by 1928 the dominant clutch type was plate, but for a few years afterward the market split between single plate and double plate. In the case of the drive type, the spiral bevel acquired absolute dominance by 1922; but from 1926 on it had to compete against the hypoid type. By 1940 the latter was present in 80 percent of all models.

2.4.3 Estimating Hedonic Regressions

We estimate semilog hedonic regressions using both current and CPI-deflated prices for every pair of adjacent years and include a dummy for the later year in the pair.[20] Tables 2.3–2.5 show the results. Since we are interested primarily in computing quality-adjusted price indexes, we content ourselves here with pointing out certain salient features of the regressions without analyzing them in comprehensive detail.

The coefficient of wheelbase is strikingly stable across most of the regressions, and strongly statistically significant throughout. The coefficient of displacement (i.e., power) is also quite steady during the 1920s, though it is less stable both before and after. The systems variables are for the most part significant, but aside from a few relatively short-lived instances (e.g., CLPLATE from 1914 to 1920), their coefficients vary a great deal.[21]

Note that the R^2 values are high and systematically increasing over time, rising from about .70 in the years 1910–20 to about .90 in the years 1930–40.

20. Henceforth we refer to the coefficient on the dummy for the later year as the hedonic coefficient. Recall that adjacent years in our database are in fact two years apart.

21. We will not attempt to interpret the magnitudes of particular coefficients here. The literature appears to be divided on whether this is a useful activity; and it would in any case require a technical discussion not germane to the goals of this section.

Table 2.3 **Hedonic Price Regressions for Automobiles (semilog) 1906–1920**

	1906–08	1908–10	1910–12	1912–14	1914–16	1916–18	1918–20
D-CURRENT[a]	−0.36	−0.26	−0.09	−0.13	−0.27	0.15	0.31
	(−9.4)	(−8.8)	(−6.1)	(−8.5)	(−8.3)	(6.8)	(17.0)
D-CONSTANT[b]	−0.36	−0.29	−0.13	−0.17	−0.35	−0.17	0.03
	(−9.4)	(−10.0)	(−9.0)	(−11.0)	(−11.0)	(−7.8)	(1.5)
WHEELBASE	0.04	0.03	0.02	0.03	0.046	0.05	0.04
	(16.0)	(19.0)	(14.9)	(20.0)	(45.0)	(45.0)	(21.0)
HP	0.008	0.015					
	(3.3)	(11.0)					
DISPLACE			0.002	0.002	0.00	0.00	0.009
			(18.7)	(18.0)	(0.0)	(0.0)	(5.3)
RAXLEF			0.076	0.002	−0.08	−0.07	−0.04
			(4.9)	(0.1)	(−4.1)	(−3.6)	(−1.9)
CLDISC			0.05	0.08			
			(3.7)	(5.5)			
CLPLATE					−0.14	−0.11	−0.11
					(−3.2)	(−4.5)	(−6.0)
DRSBEVEL					0.099	0.06	0.18
					(2.8)	(2.1)	(5.7)
SPHELLIP			0.097	0.074	−0.046	0.04	0.0005
			(5.7)	(3.7)	(−1.5)	(1.6)	(0.0)
R^2	0.75	0.70	0.70	0.70	0.69	0.73	0.77
MSE	0.119	0.099	0.087	0.087	0.113	0.111	0.089
N	356	1,150	1,798	1,710	1,271	1,115	1,165

Note: Numbers in parentheses are t-statistics.

[a]Second-year dummy, current prices.

[b]Second-year dummy, constant (CPI-deflated) prices.

Table 2.4 **Hedonic Price Regressions for Automobiles (semilog) 1920–1930**

Variable	1920–22	1922–24	1924–26	1926–28	1928–30
D-CURRENT[a]	−0.09	−0.15	−0.10	−0.07	−0.13
	(−5.0)	(−8.7)	(−6.3)	(−4.9)	(−11.0)
D-CONSTANT[b]	−0.085	−0.17	−0.14	−0.04	−0.11
	(−4.5)	(−9.8)	(−8.4)	(−2.7)	(−9.0)
WHEELBASE	0.05	0.05	0.05	0.04	0.035
	(25.0)	(30.0)	(36.0)	(39.0)	(37.0)
DISPLACE	0.0007	0.001	0.001	0.002	0.003
	(4.0)	(5.3)	(9.5)	(17.0)	(22.0)
RAXLE50F	0.005	−0.0008	0.008	0.13	0.04
	(0.3)	(−0.5)	(3.9)	(6.2)	(2.5)
CLDISC	0.06	−0.002			
	(2.9)	(−0.09)			
CLPLATE			0.044	0.006	
			(2.5)	(0.3)	
DRSBEVEL	0.16				
	(3.2)				
SPHELLIP	−0.07	−0.05	−0.05	−0.07	
	(−3.6)	(−2.5)	(−2.4)	(−2.8)	
R^2	0.72	0.75	0.80	0.83	0.86
MSE	0.099	0.099	0.079	0.065	0.057
N	1,234	1,403	1,286	1,370	1,649

Note: Numbers in parentheses are t-statistics.

[a]Second-year dummy, current prices.

[b]Second-year dummy, constant (CPI-deflated) prices.

Table 2.5 **Hedonic Price Regressions for Automobiles (semilog) 1930–1940**

Variable	1930–32	1932–34	1934–36	1936–38	1938–40
D-CURRENT[a]	−0.2	−0.08	0.01	0.10	−0.05
	(−15.0)	(−4.2)	(0.5)	(9.7)	(−2.4)
D-CONSTANT[b]	−0.003	−0.06	−0.02	0.15	−0.04
	(−0.3)	(−3.1)	(−1.3)	(8.7)	(−2.1)
WHEELBASE	0.04	0.04	0.04	0.03	0.016
	(37.0)	(28.0)	(22.0)	(21.0)	(10.7)
DISPLACE	0.002	0.0003	0.03	0.004	0.005
	(12.0)	(1.2)	(13.0)	(20.0)	(23.0)
RAXLE50F	−0.09	−0.16	0.04		
	(−4.2)	(−5.2)	(1.4)		
BRIHYDRA	0.06	0.02	−0.11		
	(3.8)	(0.8)	(−4.8)		
CLSPLATE	0.05	−0.15	−0.05		
	(2.5)	(−6.1)	(−1.6)		
DRHYPOID		0.22	−0.05	−0.03	−0.095
		(7.0)	(−2.1)	(−1.9)	(−4.2)
R^2	0.87	0.89	0.92	0.89	0.83
MSE	0.066	0.064	0.043	0.052	0.072
N	1,589	958	787	832	800

Note: Numbers in parentheses are t-statistics.

[a]Second-year dummy, current prices.

[b]Second-year dummy, constant (CPI-deflated) prices.

Likewise, the mean square error (MSE) of the regressions systematically decreases over time. This pattern may be seen more clearly in the course of the average MSE decade by decade:

Decade	Average MSE
1906–10	0.1100
1910–20	0.0974
1920–30	0.0798
1930–40	0.0594

It is thus quite evident that the fit of the hedonic regressions improves over time. It is not entirely clear why we should observe this pattern. One possible explanation is that the looser fit in the earlier years reflects greater technological heterogeneity and so a greater number of omitted aspects of quality. Subsequent convergence toward standard designs varying principally only in size and power would by itself then lead to improving fit. It is also possible that with the increasing maturity of the market for automobiles, the preferences of consumers became increasingly well defined and the consumers themselves increasingly well informed. Both of these factors would have worked to force prices more and more into line with the observed attributes. It would be interesting to see whether the phenomenon of a tighter fit of the hedonic regression as an industry evolves from infancy to maturity is also found in other markets.

2.5 Quality-Adjusted Price Indexes

In this section we compute quality-adjusted price indexes for automobiles, decompose them into two components corresponding to process and product innovation, and break down the entire period into more homogeneous subperiods. We also compare them to parallel indexes for computers. Finally, we couple our series to Gordon's (1990) for the postwar decades so as to see the industry's history whole.

2.5.1 Simple Quality-Adjusted Price Indexes

On the basis of the hedonic coefficient, denoted hereafter by α, we compute a quality-adjusted percentage price change as follows:

$$\%\Delta\text{QAPrice} = \exp\alpha - 1.$$

Here QA stands for quality-adjusted, $\%\Delta$ for percentage of change.[22] We calculate $\%\Delta$QAPrice both for α's estimated on the basis of current prices and for α's estimated on the basis of CPI-deflated prices. We then construct corresponding quality-adjusted price indexes with the results shown in table 2.6.

22. Note that for small values of α, $\%\Delta\text{QAPrice} \cong \alpha$. But as α grows larger in absolute value, so does the difference between $(\exp\alpha - 1)$ and α.

Table 2.6 **Quality-Adjusted Price Indexes for Automobiles: 1906–1940**

	Rate of Change Using		Index Using	
Year	Current Prices	Constant Prices	Current Prices	Constant Prices
1906	—	—	100.0	100.0
1908	−0.30	−0.30	70.0	70.0
1910	−0.23	−0.25	54.0	52.4
1912	−0.09	−0.12	49.3	46.0
1914	−0.12	−0.16	43.3	38.8
1916	−0.24	−0.30	33.1	27.4
1918	0.16	−0.16	38.4	23.1
1920	0.36	0.03	53.4	23.8
1922	−0.09	0.09	47.9	25.9
1924	−0.14	−0.16	41.2	21.9
1926	−0.10	−0.13	37.3	19.0
1928	−0.07	−0.12	34.8	16.7
1930	−0.04	−0.10	33.4	15.0
1932	−0.18	0.00	27.4	14.9
1934	−0.08	−0.06	25.3	14.0
1936	0.01	−0.02	25.5	13.8
1938	0.19	0.16	30.2	16.0
1940	−0.05	−0.04	28.8	15.4
Annual average 1906–1940	−0.03	−0.05		

Note: Constant prices are CPI-deflated (1993 = 100).

The main findings are as follows. First, quality-adjusted prices (based on CPI-deflated prices) fell at an average rate of slightly more than 5 percent per year from 1906 to 1940, thus halving every thirteen years. This is by absolute standards quite a substantial pace. In terms of constant 1993 dollars, it means that the average price of a car of constant quality was $52,600 in 1906 and fell to just $8,100 by 1940. To put this in perspective, if the industry had continued to innovate at the same rate from 1944 to 1994, a car by then would have cost just $582 on a quality-adjusted basis.

Second, as is to be expected, the rate of change of quality-adjusted prices was generally larger in absolute value when we used CPI-deflated prices than when we used current prices. The exception is periods of marked deflation, during which automobile prices—like the prices of many durables—dropped more slowly than the CPI.[23] Third, we ran different variants of the hedonic regressions and constructed the corresponding indices in order to ascertain the role played by the inclusion of the variables representing the five engineering systems. The results (not shown in the tables) indicate that their inclusion does

23. Thus in 1922 and 1932 the %ΔQAPrice based on current prices shows large declines whereas the %ΔQAPrice based on CPI-deflated prices either increases or shows no decline. The largest discrepancies between the two occurred in 1918 and 1920 because of the post–World War I inflation.

make a difference, but for the most part it is a small one—in the range of 0.5 to 1.5 percentage points per year in the computation of %ΔQAPrice.[24]

2.5.2 Process versus Product Innovation

We next compute a rate of quality change, defined as a residual:

$$\%\Delta\text{Quality} = \%\Delta\text{Price} - \%\Delta\text{QAPrice}.$$

If the attributes of cars remain constant, %ΔPrice is exactly equal to %ΔQAPrice, and %ΔQuality must equal zero. Suppose, on the other hand, that cars improve. Then %ΔQAPrice is strictly less than %ΔPrice. We might call the difference—that is, %ΔQuality—pure quality change. If there is some technical advance then this difference would be positive. (In this case %ΔQAPrice would be negative, since it refers to the quality-adjusted price decline.) Notice that %ΔQuality can take negative values if quality-adjusted prices drop less or rise more than unadjusted prices. That would be the case, for example, if prices did not change but some cars displayed fewer of some attributes that were positively valued (or, more precisely, that show a positive coefficient in the hedonic regression).

The series is displayed in table 2.7. The 5 percent average annual decline of quality-adjusted prices can be decomposed as follows. Prices by themselves (CPI-defaulted) dropped at the rate of 3 percent per year. The residual "quality" therefore increased at a rate of 2 percent. If we identify constant-quality price change with manufacturing economies and quality change, as we have defined it, with design improvements, then these numbers suggest that 60 percent of the decline in quality-adjusted prices was due to process innovation and only 40 percent was due to product innovation or quality change per se.

This partition of the overall quality-adjusted price decline into a product-innovation and a process-innovation component should be regarded cautiously (see also Griliches 1961). Many modern manufacturing economies, for example, come from simplifying designs (see, for example, Whitney 1988), and a reliable decomposition would therefore have to study specific innovations. And prices can certainly fall for a variety of reasons, among them increased competition and lower input prices. But the identification with process innovation seems plausible because of the dramatic economies offered by the development and diffusion of mass-production methods. There can be no doubt that the set of techniques grouped under the umbrella term "mass production" constituted one of the most important innovations in manufacturing methods of all time and had tremendous consequences in terms of unit costs, scale, and

24. The one important exception is 1914–16. During that period there was a big drop in prices (amounting to −33 percent in CPI-deflated prices), but at the same time there was a significant downsizing of cars (i.e., both mean wheelbase and power declined a great deal). As a result, the drop in quality-adjusted prices is less than that of unadjusted prices (−0.30 versus −0.33). If one were to exclude wheelbase and power from the regression, but include the systems, then the quality-adjusted price decline jumps to −54 percent!

Table 2.7 Price and Quality Indexes for Automobiles (in constant 1993 dollars)

Year	Mean Price	Mean QAPrice	%ΔPrice	%ΔQAPrice	%ΔQuality
1906	52,640	52,640			
1908	46,640	36,848	−0.11	−0.30	0.19
1910	39,860	27,583	−0.15	−0.25	0.10
1912	41,400	24,214	0.04	−0.12	0.16
1914	44,242	20,424	0.07	−0.16	0.23
1916	29,483	14,423	−0.33	−0.30	−0.03
1918	24,875	12,160	−0.16	−0.16	0.00
1920	24,566	12,528	−0.01	0.03	−0.04
1922	27,146	13,634	0.11	0.09	0.02
1924	22,732	11,528	−0.16	−0.16	0.00
1926	22,082	10,002	−0.03	−0.13	0.10
1928	21,241	8,791	−0.04	−0.12	0.08
1930	20,702	7,896	−0.03	−0.10	0.07
1932	25,803	7,843	0.25	0.00	0.25
1934	23,236	7,370	−0.10	−0.06	−0.04
1936	17,842	7,264	−0.23	−0.02	−0.21
1938	19,036	8,422	0.07	0.16	−0.09
1940	16,565	8,107	−0.13	−0.04	−0.09
Annual			−0.03	−0.05	0.02

production capabilities. The drop from, say, the $2,000–$3,000 cars of the early years to the less-than-$500 Ford Model T would never have been possible with the craftlike production and assembly methods that prevailed early in the century.

It remains to be established, however, precisely how much of the industry's overall price drop can be attributed to the diffusion of mass production and what exactly the causal link was. Casual evidence suggests that the relationship was very nonlinear, perhaps because of the interplay between innovation and competition. Recall that prices dropped a great deal in the immediate aftermath of Ford's introduction of mass production. Recall also that this was a period in which Ford was the only producer to operate in this fashion. We speculated above that the generalized drop was due to competitive pressures brought about by Ford's drastic price reductions. That the downward trend in prices continued along with the diffusion of mass production is certainly consistent with this explanation, but it is not clear how closely synchronized the two processes were.[25] It would also be interesting to see whether the steep and sustained drop in prices experienced by the automobile industry over more than three decades is typical of new industries along their trajectory toward maturity or whether it was unique.

25. Nor can it be at this time. Surprisingly little is actually known about the diffusion of these methods on the firm and establishment levels. See Raff (1991) and Bresnahan and Raff (1993) for a start.

Table 2.8 **Rates of Change of Automobile Prices: Subperiods**

Subperiod	Rate of Change
	%ΔQAPrice
1906–18	−0.22
1918–22	0.06
1922–30	−0.13
1930–40	0.01
1906–40	*−0.10*
	%ΔQuality
1906–14	0.17
1914–24	−0.01
1924–32	0.12
1932–40	−0.11
1906–40	*0.04*

2.5.3 Quality-Adjusted Price Changes over Subperiods

Price changes averaged over the entire period conceal significant and interesting differences across subperiods. In this section we present the bare facts. We leave for future work detailed examination and explanation of the differences.

As table 2.8 reveals, one can clearly distinguish four periods in terms of %ΔQAPrice and %ΔQuality. Note that the partition is not exactly the same for the two measures. Most of the innovation appears to have occurred very early on (i.e., 1906 through either 1914 or 1918, depending on which series one uses). Moreover, the highest rates of quality change occurred at the very beginning (1906–14). This is undoubtedly the portion of our period in which the greatest proportion of entrepreneurs were engineers or mechanics by training, knowledge spillovers were all-pervasive, and design bureaucracies were shallowest. Whatever the mechanisms may have been, the pattern lends further support to the conjecture that it is indeed in the course of the emergence of a new industry that the largest strides in product innovation are made.[26] An important implication of this is that if one leaves out those early stages in computing quality-adjusted price indexes, one is bound to grossly underestimate the welfare effects of product innovation.

In order to gain some perspective on the observed rate of innovation in cars during the initial period, it is worth comparing it to the rate in what might be regarded as the parallel period for personal computers, namely 1982–88. As reported in Berndt and Griliches (1993), the average rate of quality-adjusted price decline in that industry during that period was somewhere between −0.20 and −0.30 percent per year (depending on the sort of estimate used). For cars, our results show a figure of about half that size (−0.11 percent per

26. Trajtenberg (1990) documents this pattern for the case of computerized tomography (CT) scanners.

year for 1906–18, −0.14 percent per year for 1906–14). This is quite remarkable considering that the case of personal computers is widely regarded as extreme in its rate of real-price decline. The decline for personal computers derived primarily from a long and steady series of dramatic improvements in integrated circuit—in particular, microprocessor—design and manufacturing capabilities. No major automobile component experienced such sustained dramatic price/performance declines.[27] Yet the entire choice spectrum of cars displayed 11–14 percent yearly rates of quality-adjusted price drops for roughly a decade!

The biggest discrepancy between the picture presented by %ΔQAPrice and that by %ΔQuality is in the period 1914–18. During those years prices came down steeply, but measured quality stagnated or even worsened a little. As already mentioned, those years saw a substantial downsizing of cars. In the context of hedonic measurement, this registers as quality decline. A similar phenomenon happened in 1936, when a significant price drop (of over 20 percent) was more than offset by downsizing, resulting in a measured quality-change residual of −21 percent.[28] However, it is doubtful that the reduction in the mean of some of the measured attributes during those episodes corresponds to welfare loses of the magnitude suggested by the hedonic computations. We discuss why this is so in section 2.6 below.

Another interesting fact to notice is the dramatic changes from period to period and the cyclical pattern that they follow. This could in principle be a manifestation of economies of scale in production or of competition in the product market driving profit margins. This too is a finding in want of further research and interpretation.

2.5.4. A Longer Horizon

It is natural to want to place the main findings of this section in the context of a more extended history of the industry. The obvious way to do this is to link the appropriate series of our data to the recent series of Gordon (1990), which runs from just after the war through the early 1980s. Since Gordon's series also derives from unweighted regressions, it is in fact appropriate to link the two directly.[29] The linking can be accomplished using numbers relating 1937 and 1950 cross sections from Griliches (1961). Table 2.9 gives the combined series.[30] Figure 2.3 illustrates.

It would be in the spirit of the literature to give a detailed interpretation to

27. T. L. De Fazio, Charles Stark Draper Laboratories, Cambridge, Mass., personal communication.

28. This happened again after 1975 (Gordon 1990). In that instance, the improvement in fuel economy offset the estimated value of the decline in size. It is unfortunate that no broadly based data on model fuel economy exists for the period studied in this paper.

29. His regressions do not incorporate our systems approach, but much of the explanatory power in both is carried by the common variables.

30. The break in the series is ultimately due to the cessation of automobile production during World War II.

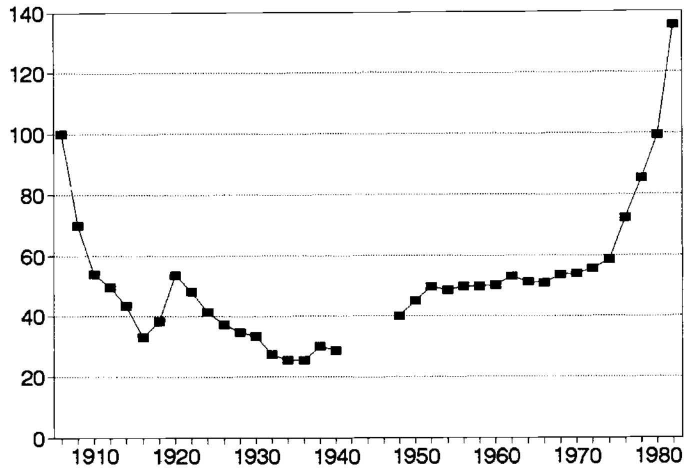

Fig. 2.3 Quality-adjusted price index 1906–1982 from current-dollar data (1906=100)

Table 2.9 Combined Hedonic Price Index

Year	Index	Year	Index	Year	Index	Year	Index
1906	100.0	1934	25.3	1956	49.7	1970	53.9
1908	70.0	1936	25.5	1957	50.3	1971	57.8
1910	54.0	1938	30.2	1958	49.7	1972	55.6
1912	49.3	1940	28.8	1959	50.8	1973	54.5
1914	43.3			1960	50.3	1974	58.4
1916	33.1	1947	34.7	1961	50.8	1975	68.5
1918	38.4	1948	39.9	1962	52.8	1976	72.0
1920	53.4	1949	46.9	1963	51.8	1977	74.3
1922	47.9	1950	45.0	1964	51.3	1978	85.4
1924	41.2	1951	48.8	1965	50.3	1979	88.9
1926	37.3	1952	49.7	1966	50.8	1980	99.2
1928	34.8	1953	49.7	1967	51.3	1981	124.9
1930	33.4	1954	48.3	1968	53.4	1982	135.3
1932	27.4	1955	50.8	1969	52.3	1983	140.8

Note: The coefficient on the variable *D* in table 4 of Griliches (1961) was used to splice the third column of our table 2.5 and column 6 of table 8.8 in Gordon (1990).

this figure. But the underlying series are in terms of current prices and the radical changes in the general price level that occurred over this extended period suggest deflating by the CPI first. This yields the series illustrated in figure 2.4. The explosion at the end of the series in figure 2.3—proportionately roughly as large as the declines of the early years—is revealed to be for practical purposes entirely due to inflation. The overwhelming bulk of the quality-adjusted price decline in this industry came in a tremendous burst before the

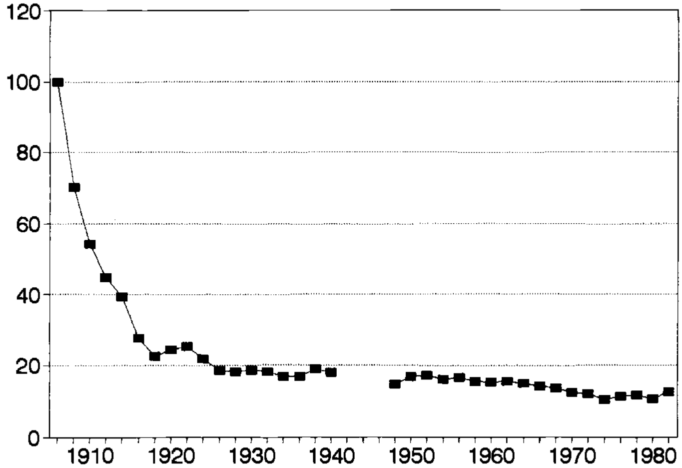

Fig. 2.4 Quality-adjusted price index 1906–1982 deflated by the Consumer Price Index (1906=100)

1920s. By the time the Depression was over, so was most of the story. Computations of growth rates averaged out over very long intervals can indeed miss the most salient details.

2.6 Potential Biases

The fact that our estimates are based on unweighted hedonic regressions may introduce biases in the quality-adjusted price indexes, primarily in those subperiods that experienced pronounced shifts in the structure of the market. The main concern is that our indexes may understate the extent of the real price reduction associated with the introduction and diffusion of mass-production methods and the concomitant ascendancy of low-end models, primarily the Ford Model T. The issues here are interesting and worth exploring.

There are two intertwined but nevertheless distinct aspects to the Model T phenomenon. First, true mass-production methods were deployed in manufacturing it. These methods allowed Ford to realize vast economies of scale and concomitant cost savings which emerged in substantial part as steep price reductions. The low prices sustained the mass market. Second, the Model T was a smaller, simpler, less powerful, and less luxurious car than virtually any other car of its time. These two aspects are intimately connected.

It is quite clear that if the Model T had been produced with the craft methods that were prevalent in the industry at the time, its price would have been much higher. In fact, hedonic regressions including a dummy variable for Ford in the early period show large negative coefficients on the dummy, in some years amounting to a price discount of 40 percent. That is, the Ford Model T was radically cheaper than what was warranted by the mere fact that it was smaller, simpler, and less powerful than other cars in the market. This was the force of mass production.

On the other hand, it seems equally clear that introducing mass-production methods in manufacturing the higher-end models of the time, even if it had been technologically feasible, would have not rendered cars nearly as low-priced as they needed to be to hit the more elastic segments of demand. In fact, the mass market revealed itself only as the price dropped to about $500, about one-sixth of the mean price of cars in preceding years. In other words, the adoption of mass-production methods could be justified only if one could produce in very large quantities, and such cars could find a market only if they were to be very cheap. This, in turn, necessitated the design of a small, stripped-to-the-bone type of car. Similarly, as the mass-production methods spread to other manufacturers, they were applied first (and, for quite a while, only) to cars at the low end or, more precisely, to small, simple cars designed specifically with these demand and production relationships in mind.

What are the implications of these facts for the construction (and interpretation) of our price indexes? There are two, one related to the fact that we do not have quantity data, the other to the inherent limitations of the hedonic methods in these circumstances. We discuss them sequentially in the remainder of this section.

2.6.1 Lack of Quantity Data: Biases and Remedies

Our lack of detailed quantity data, which obliges us to base our calculations on nothing more complex than unweighted hedonic regressions, might cause a serious underestimate of the price fall that took place as mass-production methods were introduced and the Ford Model T captured a large share of the total market. One can think of this as a sampling problem. As the market composition shifted dramatically toward the low end, we keep sampling according to the old frame of reference in which all models received their initial—implicitly, equal—weights. How big a problem is this? To assess the extent of the bias, we bring in two additional sets of numbers. These are a separate index for Ford cars alone, which we have calculated for this purpose, and the automobile component of the Producer Price Index (PPI) of the period, a component which is based primarily on mass-produced cars.

The simplest way to assess the extent of the bias without resorting to unavailable broadly based quantity data is to take the lowest-priced Ford as a reasonable proxy for the mass-market car of each year, create a quality-adjusted price index for Ford, and observe how it compares to our QAPrice index. Figure 2.5 does this. It was convenient to start the Ford series with a figure for 1910, so the comparison runs from 1910 to 1940.

It is important to note that Ford sold just one basic design, with only minor variations, from the beginning of the period shown here through 1927. The first epoch in the Ford series is a long decline, punctuated only by a spike in

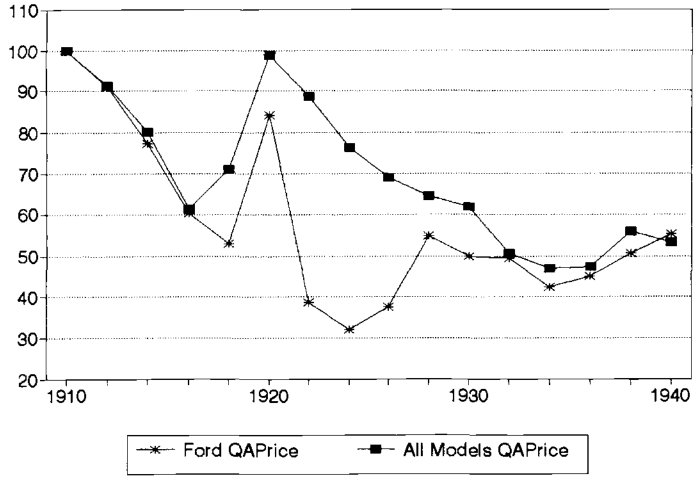

Fig. 2.5 Ford quality-adjusted price versus all models quality-adjusted price (1910=100)

the immediate postwar years which represents the sharp but transitory postwar inflation, the company's financial crisis, and its desperate—if in the end quite effective—measures to avoid insolvency.[31] During this decade and a half, Ford cars were produced with unusually capital-intensive methods.[32] Output exploded and economies of scale were exploited relentlessly. By 1926, the design was unchanged but the market was not. It was in this period that Ford acquired, for the first time, serious competition for the low end of the market.[33] The Model T clearly needed to be replaced, and the late 1920s at Ford were the epoch of the more sophisticated Model A. Production ramped up and costs fell, albeit more slowly than before. By the mid-1930s, bolstered by the Depression-induced shakeout of smaller-scale producers, all three low-end makes were moving upmarket in attribute space, and the final series of Ford numbers reflects this.

Figure 2.5 faithfully depicts these developments. We can see that the divergence between the unweighted series and Ford's starts in 1918 and goes on until 1930, with Ford's showing—as expected—a lower index. But it is in the mid-1920s that the difference becomes very pronounced, with the Ford index reaching a low of less than one-half the level of the unweighted index in 1922–24. The mechanics of this are quite simple. Our unweighted index converges back toward its 1916 level quite slowly from the postwar inflation spike. The Ford series, by contrast, positively vaults back onto the track of the scale-

31. On the company's postwar troubles, see Nevins and Hill (1957).

32. In the 1920s the Ford mother plant was often said to be the largest single industrial establishment in the world.

33. This came from General Motors' Chevrolet (circa 1924) and Chrysler's Plymouth (1928).

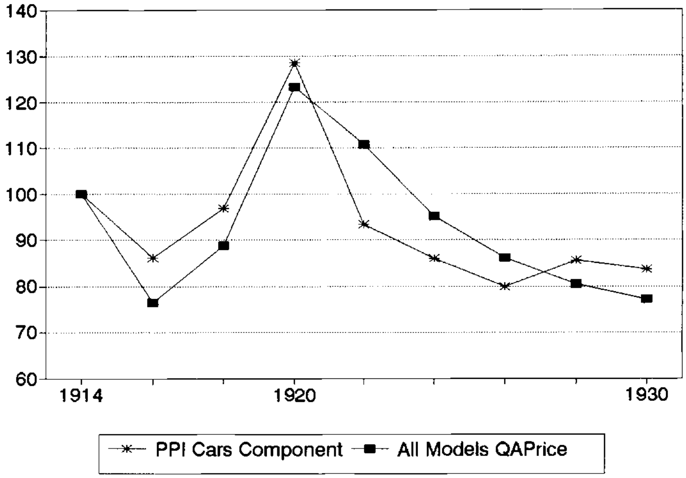

Fig. 2.6 Producer Price Index cars component versus quality-adjusted price 1914–1930 (1914=100)

driven economies. It comes back up mid-decade as consumer tastes shifted toward the less spartan models the rest of the manufacturers were by then making. Two points thus emerge. First, it is when the market is experiencing dramatic changes in the composition of its output that the lack of quantity data proves most awkward for the hedonic method. Second, however, the unweighted index tells quite an accurate story over the long run of our period.

Figure 2.6 presents a similar comparison, but this time with the automobile component of the PPI. This was quantity-weighted average of the prices of specific models of six manufacturers, representing the broad sweep of the market.[34] This is in effect a selective quantity-weighted index uncorrected for changes in quality. The most important feature of the figure is that the two series have the same broad qualitative features. But contrary to Gordon's findings for the post–World War II period, there is no trending bias to the PPI component here. The relative positions of our index and the PPI series change as downsizing or quality-enhancement in the ordinary sense dominate. In this, our index is surely superior. The figure also shows our index to be off in periods of market composition change. This is just what we observed with the Ford series.

2.6.2 Potential Biases due to Downsizing

The second potential source of bias stems from the other aspect of mass production, namely that it involved manufacturing low-end cars. In fact, from

34. The manufacturers were Buick, Cadillac, Chevrolet, Dodge, Ford, and Packard. See, e.g., U.S. Bureau of Labor Statistics (1929, 2 and table 9).

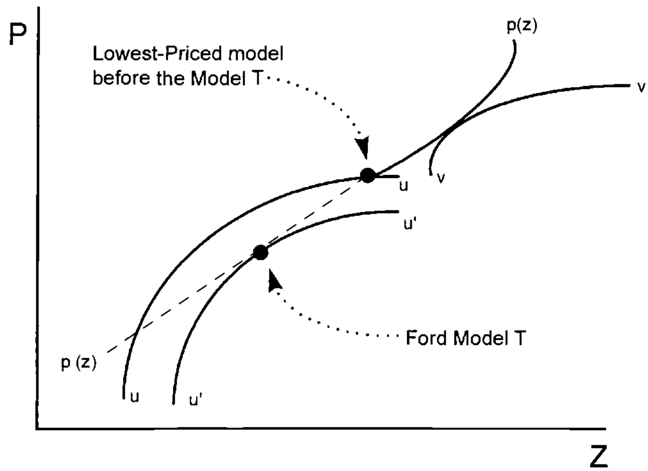

Fig. 2.7 Downsizing bias

the middle of the second decade of the twentieth century to the middle of the third, there was a pronounced downsizing trend in the mix of models offered in the market, with a concomitant reduction in prices. (A second downsizing wave, less pronounced, occurred in the late 1930s.) As we have remarked, it remains to be established how precisely this relates to the advent of mass production since Ford alone introduced those methods to begin with and Ford models constituted only a tiny fraction of the population of models. Clearly, these issues can be properly dealt with if and only if extensive quantity data become available.

But the problem in this context is that the hedonic method cannot (and was never meant to) assess the trade-offs in utility between a reduction in measurable quality (for example, HP) and the price reduction. All it can do is tell whether the prices fell on average more or less than what the reduction in quality would have warranted and translate that measure into a price index. Is such an index an accurate representation of the underlying changes in consumers' welfare as a consequence of the introduction of low-end cars? Without more information it is impossible to say, but there is good reason to suspect not.

Consider the hypothetical situation depicted in figure 2.7. Price is measured on the vertical axis (P), a positively valued attribute such as HP on the horizontal (Z). In the base period, the hedonic function is the solid line $p(z)$. The indifference curve $u-u$ represents consumers who buy the lowest quality-price combination but are not "satisfied": satisfaction requires tangency between the indifference curve and the hedonic surface. (Compare their situation with that of the consumers represented by the indifference curve $v-v$.) In the second period, new low-end models appear. As a consequence, the $u-u$ type of consumers can attain a higher utility level, $u'-u'$. A hedonic quality-adjusted price index might decrease somewhat, show no change at all (as shown in figure 2.6), or even increase. In any case, it will be biased upward: the distance between $u-u$ and $u'-u'$, which is a rough approximation for the welfare gain associated with the change, will always exceed the distance between the old and new hedonic curves. Indeed, the overall bias may be very large if consumers of the $u-u$ type make up a large fraction of the market. This seems likely to have been the case in the late part of the second decade of the twentieth century and the first half of the third decade. Without quantity data and the more demanding computational methods, however, we cannot assess the magnitude of the bias. We can only identify the periods in which this bias is likely to occur and interpret hedonic-based results for those periods as lower bounds for the true quality-adjusted price reductions.

2.7 Conclusion

Most of the change in quality-adjusted prices (based on CPI-deflated prices) of American automobiles between 1906 and 1983 occurred during the period studied in this paper. Between the years 1906 and 1940, quality-adjusted prices fell at an average rate of 5 percent per year, thus halving every thirteen years. That is a very brisk pace. In the first eight to twelve years of the period, the pace was even brisker, about one-half the size of the best recent estimates for the personal computer industry. We find this one-half an intriguingly high fraction for an industry that in its time wrought equally radical changes on society and on the feasibility of other innovations. Methodological reflections suggest that the true fraction may be even higher.

Our measured decline can be divided into price and quality components. Prices themselves (CPI-deflated) dropped at a rate of 3 percent, whereas quality as we measure it increased at a rate of 2 percent per year. This suggests that 60 percent of the decline in quality-adjusted prices was due to process innovation and only 40 percent to product innovation or quality change per se.

One innovation of this study was to include much more detail about the mechanical aspects of the vehicles in the regressors. Regression results, some reported here and some not, indicate that inclusion of systems variables does make a difference. For the most part, however, the difference is a small one (about 1 percentage point in the computation of %ΔQAPrice). This may grow larger as researchers' sophistication about engineering issues grows.

These estimates all derive from unweighted regressions. Comparisons of the unweighted index with an index derived from low-end Ford models, a reasonable proxy throughout the period for the mass market, reveals a significant divergence for a brief (transitional) period but otherwise fairly thoroughgoing conformity. Thus long- and even medium-term measures of the sort discussed above would be unaffected by the choice of index. Comparison of our index with a quantity-weighted Bureau of Labor Statistics index that does not correct

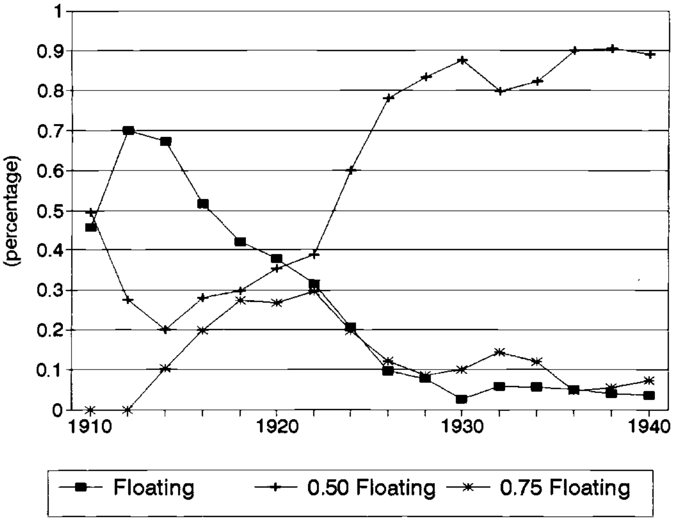

Fig. 2A.1 Rear axle designs 1910–1940

for quality change reinforces this point and also underlines the importance of correcting for quality.

This paper is a first quantitative glimpse into one of the most dynamic and interesting periods in the history of modern industrial sectors. A number of substantive questions clearly worthy of further research have emerged. Pursuing most of them would require a database incorporating quantity data. More light may thus be shed in future work.

Appendix
The Evolution of System Designs

Figure 2A.1 shows the initial division of rear axle designs between the floating and the lighter and cheaper half- (or semi-) floating design. The main design issue here is how the weight of the car is distributed over the axle.[35] Initially, the semifloating approach lost ground to the fully floating, presumably as it became clear that contemporary single bearings were inadequate to carry the loads and stresses involved. As incremental innovations in bearing design emerged, the proportion of semi- and three-quarters-floating designs in the population grew at the fully floating's expense; finally the bearing innovations

35. For details and some drawings, see Newcomb and Spurr (1989, 268–70).

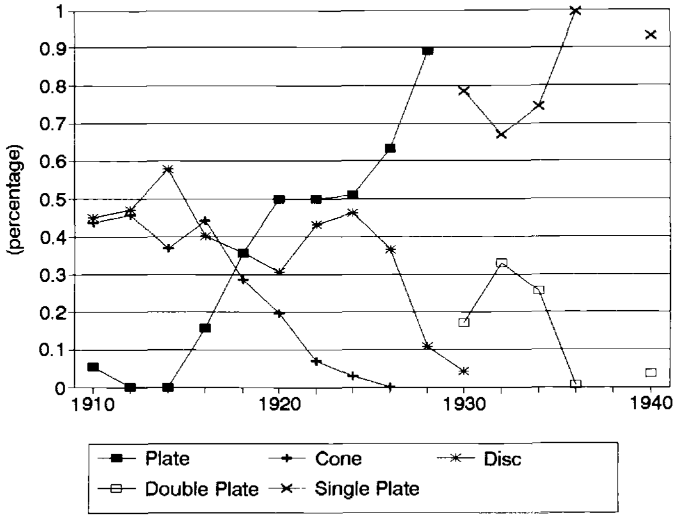

Fig. 2A.2 Clutch designs 1910–1940

seem to have been perfected, the half-floating design itself was perfected, and it essentially drove the others out of the population entirely.

The population of clutch types is displayed in figure 2A.2. There were initially a number of competing approaches (and in principle a number of variants of each). The cone design was familiar to machinists and in that sense accessible. But the mechanism needed regular cleaning and adjustment, engagement was abrupt, and the heaviness of the mechanism made gear changing difficult. The plate family did not have these problems. Initially, inadequacies of the facing materials made single-plate clutches inappropriate for relatively heavy cars. The decline of the multiplate percentage in the 1930s may well represent the declining percentage of heavy automobiles. Improved facing materials probably also play some role.

Figure 2A.3, badly afflicted with missing data, shows a similar sort of rise and fall. Hydraulic brake systems were at first expensive relative to mechanical ones. (There were also engineering reasons for wanting some of the tubing to be flexible and suspicions about the tubing's integrity persisted for some time.) Relative cost may account for the relative decline in hydraulic systems' incidence in the early Depression years. But they were almost completely dominant by the end of the decade.

Drive types are the subject of figure 2A.4. This variable concerns the means by which power was transmitted to the rear axle. Chain drives were mechanically simple and common in the very earliest cars. They contributed to a smooth ride since they involved a relatively high ratio of sprung to unsprung

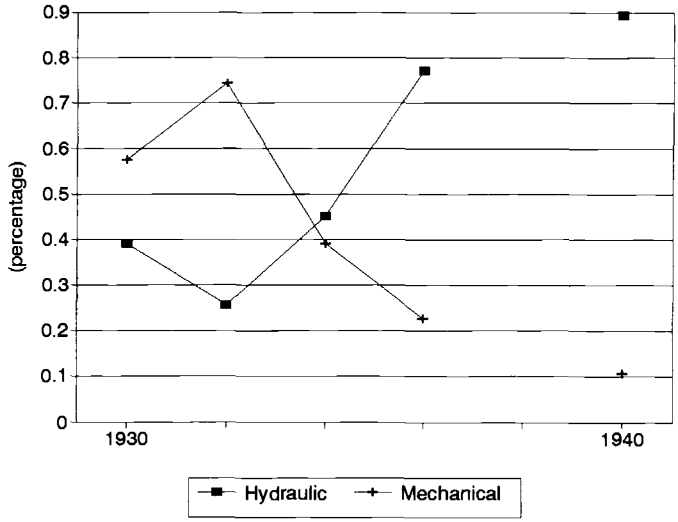

Fig. 2A.3 Brake designs 1930–1940

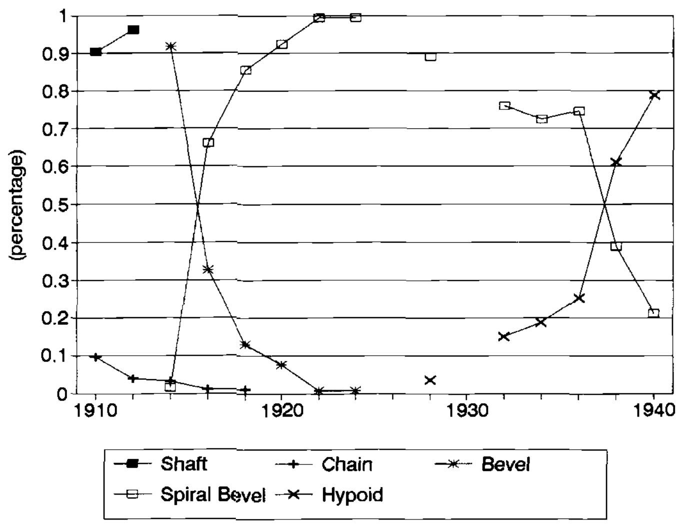

Fig. 2A.4 Drive designs 1910–1940

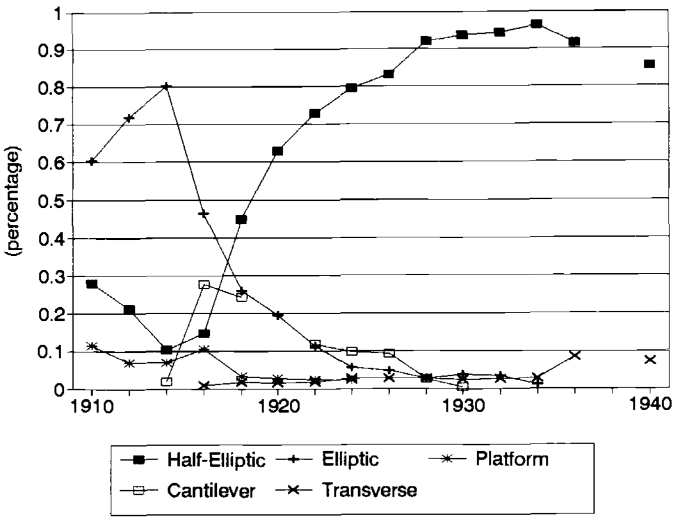

Fig. 2A.5 Spring designs 1910–1940

weight. But they were also noisy and potentially dangerous. They did not last in the population. Ordinary bevel gears had fewer of these faults but were still noisy relative to spiral-beveled gears. The spiral-bevel design emerged as the most desirable for a time but was eventually eclipsed by another innovation, hypoid gearing, that maintained the advantages of the spiral bevel and allowed the driveshaft to be lowered relative to the body.

Figure 2A.5 shows population percentages for types of springs. The transverse design seems to have been effective only for extremely light vehicles. The competition among the other designs for most of our period is best understood as being between the fully elliptic on the one hand and the half-elliptic family on the other.[36] The latter group included the half-elliptic design, the cantilever (a half-elliptic mounted in a slightly different fashion and requiring additional metal parts to constrain the axle), and the platform design (a more complex and heavier variant with no performance advantages). The issue between the full- and half-elliptics concerned how high above the axle the chassis and body had to sit. Presumably due to some combination of improving roads, evolving fashions in body styles, and the desire to take weight out of designs (so as to increase acceleration, improve fuel economy, etc.), the half-elliptic family and the half-elliptic design within it won out. In the graph, one again observes initial heterogeneity and the emergence of a dominant design.

36. Toward the end of our period one first begins to see the coil springs that were related to the development of independent front suspension.

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Comment Jack E. Triplett

Technical change can, it is well known, alter the production process or it can alter the characteristics of the product. Raff and Trajtenberg appropriately and imaginatively employ the hedonic method to explore and illuminate product-oriented technical change in automobiles from 1906 to 1940.

The economics of differentiated products concerns the production, sale, purchase, and use of the bundle of characteristics that are embodied in the product. An empirical hedonic function provides estimates of the prices of the characteristics in the bundle, and also helps, with a priori knowledge, to isolate empirically the characteristics. Because the hedonic function is determined by the technology of producing characteristics and by buyers' preferences for them (Rosen 1974), hedonic prices will be influenced in a predictable way by technical change.

The automobile hedonic model employed by Raff and Trajtenberg derives from Court (1939) and Griliches (1961), and is fundamentally the same as that in studies such as Gordon (1990), Ohta and Griliches (1976), and my own earlier work on automobiles (Triplett 1969). The hedonic functions for automobiles in this literature are primitive in many ways. They portray the complexities of automobile production or use solely through measures of carrying capacity and engine performance, plus the presence or absence of a small number of amenities. The simple automobile hedonic model is undoubtedly a better description of automobile technology in the historical period covered by Raff and Trajtenberg than it would be for more recent periods—the automobile is far more complex now, and what consumers want and expect from it is much harder to model in 1995 than in, say, 1910.[1]

Nevertheless, the simple automobile hedonic model's shortcomings need to be kept in mind in interpreting automobile hedonic measures for any period. My comments on this simple automobile hedonic model represent not so much disagreement with the reservations Raff and Trajtenberg have expressed about it (I endorse their useful discussion of engineering complexity) but, rather, differing empirical points of emphasis.

The major reservation concerns the variables in automobile hedonic functions. The entire theoretical literature on consumer price indexes rests on the implicit assumption that the consumption quantities that appear in index num-

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This paper does not represent an official position of the Bureau of Economic Analysis or of the U.S. Department of Commerce.

1. In Triplett (1990), I argued that the complexity of the modern automobile probably precludes the current use of hedonic methods in constructing automobile price indexes for the U.S. Consumer and Producer Price Indexes (CPI and PPI). In the CPI and PPI cases, alternative methods exist for constructing quality-adjusted automobile price indexes. For the 1906–40 historical period, the same alternatives to hedonic methods do not exist.

ber formulas are arguments of the consumer's utility function. It is sometimes overlooked that hedonic price indexes for consumer goods are based on exactly the same assumption: The characteristics in properly specified hedonic functions are consumption quantities that generate utility; they are arguments of a utility function that is defined on characteristics, rather than simply on goods (see Rosen 1974 for elaboration of this point with respect to hedonic functions, and Triplett 1983, 1987 for its application to hedonic price indexes).

One cannot emphasize too strongly that the simple automobile hedonic model incorporates only the roughest kinds of proxies for the true automotive services that consumers desire. Carrying capacity and performance—the major variables in the simple automobile hedonic model—provide an inadequate representation of what the automobile does for its buyer, and therefore also of what automobile companies and engineers design and produce. Obvious omissions are braking and safety characteristics, as well as comfort and other characteristics of luxuriousness. Yet, even capacity and performance characteristics are described very inadequately by the technical specifications that have been published in industry sources.

The best simple measure of passenger capacity is probably body space: the distance between the car's engine and its rear axle. This is a standard chassis dimension that is used within the industry for body-manufacturing purposes but seldom appears in industry publications. Tables of interior dimensions appear at least as early as 1928 (*Motor* 1928), yet wheelbase and overall length have been, since Court (1939), the primary measures of size in automobile hedonic functions, partly because they are consistently measured over the years and appear in most published compilations of automobile specifications.

Speed and acceleration are desired automobile performance characteristics. They were especially important in the 1906–40 period explored by Raff and Trajtenberg because performance was lower then and increments to performance much more expensive. The engine measure that is most closely related to automobile performance is torque (a measure of engine twisting power), not the horsepower the engine develops. However, torque is almost never published in statistical compilations before 1940, and even horsepower data are fragmentary for much of the period.[2] For most years, we have instead the cylinder capacity (displacement) of the engine and its "rated" horsepower.[3] Neither one is adequate for describing the trend of engine performance over time because actual power rose steadily relative to both engine displacement and rated horsepower.

2. The compilation in Naul (1978) presents, from unspecific original sources, actual horsepower for many U.S. automobile engines back to 1920. For some cars, however, data are incomplete or missing entirely.

3. Rated, or "taxable," horsepower was computed according to a formula that considered only cylinder bore. The formula was developed early in the century but was rapidly made obsolete by developments in engine design. In Great Britain, rated horsepower was used for taxation purposes. A table in *Motor* (1928) presents displacement, rated horsepower, and actual horsepower for most 1928 U.S. cars.

Beyond mere size and engine performance, a host of characteristics generates utility to the consumer of automobile services. From this perspective, it is difficult to understand why publishers selected the particular measures that appear in industry sources.[4] A few of the variables commonly tabulated (e.g., type of lubrication system, type of valves, and number of forward speeds in the transmission) have implications for some property that is important to the buyer (engine reliability, engine efficiency, and driving flexibility and performance, respectively, in the three examples cited) as well as for cost of production. A few others have implications for maintenance; a detachable cylinder head, for example, makes it far easier to grind the valves, a routine maintenance required at frequent intervals in the 1920s and 1930s, though the nondetachable head avoids all problems with cylinder head gaskets, which in the earlier years of the automobile's history were a source of mechanical failure.

No direct statistics in the published data sources measure speed and acceleration, handling ease, cornering ability, reliability, smoothness of engine, controls, and ride, and so forth. The substantial technical innovations to automobile engines, brakes, transmissions, and bodies in the 1930s, for example, vastly improved the quality of the end-of-decade car compared with the one that had been available at the beginning of the decade. All of these changes are more or less ignored in the simple automobile hedonic model, for lack of published specifications on consumer-oriented characteristics. Similar statements can be made about data for earlier decades in the automobile's history.

One can also, it is well known (see Rosen 1974), interpret the independent variables in hedonic functions as outputs of automobile producers, which means they are arguments in producers' cost functions. But the published automobile specifications are also not very closely related to technical changes that engineering departments of automobile companies were working on at the time. Ohta and Griliches (1976) make the valid distinction between what they call technical characteristics and performance characteristics. Unfortunately, the specifications that are published on automobiles are related—a little bit—to both, but do not correspond very well to either. What we have, at best, are variables that are rough proxies for the true characteristics that in a hedonic model are the outputs of producers and the arguments in buyers' utility functions.

The most one can say about the simple automobile hedonic model is (a) one hopes that the variables included in the regressions are functions of the true arguments of consumers' utility functions and producers' cost functions and (b) one hopes additionally that the function that relates the regression variables to the true characteristics is a stable one.[5] If the variables that are put into the

4. Examples of such sources are the National Automobile Chamber of Commerce ([1925] 1970) and *Motor* (1928).

5. This is not a new point. This proxy variable problem was noted in the original hedonic automobile article by Court (1939), and by Griliches (1961), and it was emphasized in Triplett (1969), and Ohta and Griliches (1976).

hedonic model—or for that matter, into the more general welfare model that Trajtenberg (1990) and others have discussed—are not the true characteristics that enter the utility function, or the outputs that define the characteristics-space cost function, empirical results will be misleading. The true utility-generating characteristics and the proxy measures incorporated into empirical hedonic functions may move differently over some periods.

This is not merely a call for better data and more research, though it is that. It has potentially serious implications for the interpretation of the work that has been done so far. Consider Raff and Trajtenberg's discussion of what they call "downsizing" of automobiles in the 1930s. Adoption of independent front suspension systems was the major innovation in automobile suspensions in that decade. In a sense, independent front suspensions are like the other innovations that are omitted from the simple automobile hedonic model: We have no adequate measures of the ride and handling improvements wrought by innovations in suspension design, and accordingly the hedonic measures miss some of the quality improvement that we would like them to measure. But there also was an indirect effect: The independent front suspension permitted moving the engine forward in the body frame, which meant there was more body space available than before for a given wheelbase size. Some designers took advantage of the changed body space–wheelbase ratio to increase passenger space, while others reduced the wheelbase, leaving passenger space unchanged. What the published automobile *specifications* show is a decline in average wheelbase, which one might incorrectly interpret as downsizing. But a good part of the wheelbase decline was not matched by a decline in the average usable carrying capacity of the car. Quite the contrary: a typical car after the introduction of the independent front suspension was more roomy inside, not less roomy.

Similar comments can be made of other periods of apparent downsizing of automobiles. The downsizing period in the U.S. industry in the late 1970s, mentioned by Raff and Trajtenberg in their discussion of the study by Gordon (1990), was striking in that it represented a substantial reduction in the ratio of external to internal automobile volume. U.S. cars within every size class were made smaller on the outside without shrinking the usable interior dimensions. And although I have not studied closely the 1915–18 downsizing period that Raff and Trajtenberg also mention, technical changes in this era reduced the size and weight of engines, especially, and made it possible to produce smaller-engined, lighter cars that gave their owners superior performance in use compared with the older, larger, and less-efficient designs. With the wheelbase and engine-displacement proxy variables used by Raff and Trajtenberg—and by all the rest of us—these technical improvements will be mismeasured.

Bias can also result from the use of either rated horsepower or cubic inches of engine displacement as a measure of automobile performance. Technical changes in the automobile engine continually raised actual developed horsepower relative to displacement and rated horsepower. A contemporary British account (Twist [1934] 1988) compared performance of the 3½-liter Bentley of the 1930s with the Bentley 3-liter model that was introduced at the beginning of the preceding decade (both model designations referred to the displacement of the car's engine). The substantial improvement in performance might have been expected, roughly, from the substantial increase in actual developed horsepower (approximately 110–120 for the later car, compared to approximately 65–70 for the earlier one), but it could not have been predicted from the relatively modest half-liter change in cylinder displacement. The Bentley was by no means unique. Increased engine performance relative to engine size was typical, not unusual, in U.S. cars as well as in those in the United Kingdom.

The examples suggest that hedonic price indexes are upwardly biased because of this proxy variable problem (i.e., they do not pick up enough of the quality changes that have occurred in cars). Empirically, upward-bias cases probably predominate in automobile hedonic studies, but that is not necessarily always the case. The difficulty is not that our proxy measures are biased in a known direction; rather, they are unreliable, so the sign of bias is not always known a priori. For complex products like the automobile, we need better data on characteristics, data that more nearly match the requirements of the theory of hedonic functions and hedonic indexes.

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