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COMPETITION AND COLLUSION IN THE AMERICAN AUTOMOBILE INDUSTRY: THE 1955 PRICE WAR*

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Movements in total quantity and in quality-adjusted price suggest a supply-side shock in the American automobile market in 1955. This paper tests the hypothesis that the shock was a transitory change in industry conduct, a price war. The key ingredients of the test are equilibrium models of oligopoly under product differentiation. Explicit hypotheses about cost and demand are maintained while the oligopoly behavioral hypothesis is changed from collusive to competitive (Nash) equilibrium. In nonnested (Cox) tests of hypothesis, the collusive solution is sustained in 1954 and in 1956, while the competitive solution holds in 1955. The result does not appear to be an artifact, since it is robust in tests against alternative specifications.

IN 1955, American passenger automobile production was 45 percent greater than in the two surrounding years, while quality-adjusted prices were lower (see Table I). Many studies of aggregate automobile demand have had difficulty explaining the 1955 events.[1] Although 1955 saw a mild macroeconomic expansion, the size of the increase in auto sales was out of proportion to earlier and later experience. The decrease in price is unlikely to reflect a demand shock in any case. Paul Samuelson summarized the situation in his famous classroom remark that he "... would flunk any econometrics paper that claimed to provide an explanation of 1955 auto sales."[2] The alternative approach of searching for a supply shock is clearly attractive. This paper provides an explanation by testing the hypothesis that there was a supply shock of a very specific form, a one-year increase in the competitiveness of conduct in the industry. It provides a model of the non-price-taking supply of differentiated products under more and less cooperative behavior, and shows how the hypothesis of competition can be empirically distinguished from that of collusion. Thus the tests of economic hypotheses in the paper are cast in precise econometric form: conduct in 1955 comes from a competitive model, in nearby years, from a collusive one.

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[1] See, for example, Chow [1960] at pp. 168–169. "The year 1955 is an exception, [to the rule that residuals are small] where we find the residual to be twice as large as the standard error."

[2] I am grateful to R. E. Hall for this anecdote.

The basis for the empirical test of the price war hypothesis is a model of short-run equilibrium in an industry with differentiated products. Here the definition of short-run is taken to reflect an important feature of the US automobile market. It is the period within which prices and quantities are set, but also the period for which firms' product lines are predetermined. The model of product differentiation is spatial, with the product space having a "quality" rather than a "location" interpretation. With fixed costs, one would expect products to be less than perfect substitutes in equilibrium. Thus even the "competitive" model investigated here is one in which there is some market power; the label refers to noncooperative conduct rather than to price-taking. In the model, firms have multiple products.

The intuition of why competitive and collusive behaviors are distinct in such a model is straightforward. If firms compete on price, price will be near marginal cost for those products for which a close, competitive substitute exists. If firms are setting price by some (tacitly) collusive means, then $(P-MC)$ for one firm's products will not depend crucially on whether their close substitutes are sold by competitors or by the firm itself. This simple intuition is an example of a much more general point about the observable consequences of noncompetitive conduct. Hypotheses about conduct have implications for the *comparative statics of price and quantity with respect to demand elasticities*. Thus even when marginal costs are taken to be unobservable, competitive and collusive conduct can be discerned from the movements in industry and firm price and quantity.

The next section reviews the history of automobile market events in the mid-fifties to motivate the specific hypotheses tested in this paper. Sections II and III lay out the models, making specific functional form assumptions about cost, demand and product type. The model is solved under two different conduct hypotheses: competitive (Nash equilibrium with prices as strategic variables) and collusive (joint profit maximizing). Section IV presents the econometric evidence on the 1955 price war hypothesis, including a discussion of robustness of the results.

I. THE FACTS TO BE EXPLAINED

Tables I and II show some aggregate indicators of US automobile market events in the mid-1950s. This section reviews these data to establish the aggregate facts the later sections will explain. In the table, the time unit is the model year, so that a row labelled 1955 is (for example) actually 1954Q4–1955Q3. Nominal data are deflated using the GNP deflator.

The first two columns of Table I show 1955 to be a high quantity, low price model year in the auto industry. Nearly half again as many cars were made in that year as in either of the surrounding years. Superior quality adjustments in the price indexes do not change the inference that 1955 was a price trough. Column 3 shows the percentage price change on earlier years with the Cagan

TABLE I

Year	(1) Auto Production[a]	(2) Real Auto Price-CPI[b]	(3) % Change Auto Price-Cagan[c]	(4) Auto Sales[d]	(5) Auto Quantity Index[e]
1953	6.13	1.01	NA	14.5	86.8
1954	5.51	0.99	NA	13.9	84.9
1955	7.94	0.95	−2.5	18.4	117.2
1956	5.80	0.97	6.3	15.7	97.9
1957	6.12	0.98	6.1	16.2	100.0

Notes: [a] Millions of units over the model year. [Source: *Automotive News.*]
[b] (CPI New automobile component)/CPI. [Source: *Handbook of Labor Statistics.*]
[c] Adjusted for quality change. [See Cagan (1971), especially pp. 232–3.]
[d] Auto output in constant dollars, *QIV* of previous year through *QIII* of named year, in billions of 1957 dollars. [Source: *National Income and Product Accounts.*]
[e] (4)/(2), normalized so 1957 = 100.

TABLE II

Year	(6) Per Capita Disposable Personal Income[f]	(7) Interest Rate[g]	(8) Durables Expenditures (Non-Auto)[h]	(9) Automakers Profits[i]
1953	1623	1.9	14.5	2.58
1954	1609	0.9	14.5	2.25
1955	1659	1.7	16.1	3.91
1956	1717	2.6	17.1	2.21
1957	1732	3.2	17.0	2.38

Notes: [f] Billions of 1957 dollars, *QIV* of previous year through *QIII* of named year. [Source: *National Income and Product Accounts.*]
[g] Three-month *T*-bill rate. [Source: *Statistical Abstract.*]
[h] Durables component of consumer expenditures minus component for automobiles and parts, billions of 1957 dollars. [Source: *National Income and Product Accounts.*]

[1971] quality adjustment. Cagan's method is based only on physically unchanging automobile models, but the hedonic regression price index reported by Griliches [1964] is similar. Real sales of autos in value terms (Column 4) expanded substantially less than unit sales. This is not to be entirely attributed to the price trough for all autos. In Column 5, I report the implicit quantity index obtained by dividing sales by the price index in Column 2, which expands substantially more than Column 4 in 1955. What is going on here is a one-year shift during 1955 to smaller, lower value cars by consumers.[3] Clearly, the data in these first five columns suggest that the supply curve for automobiles shifted down in 1955. I shall return later to the point about the shift to smaller, lower-value cars.

[3] See production by "Price Group" in *Ward's Automotive Yearbook* for 1956, p. 49, and for 1957, p. 59.

Columns 6–8 (Table II) show data from outside the auto market. The income figure shows 1955 to be a year of mild macroeconomic expansion. Interest rates were also low that year. Both of these would tend to increase demand for automobiles, a durable good. Indeed, non-auto durables expand somewhat in 1955, though they do not contract the next year as the macroeconomic boom continues. This difference between auto and non-auto expansion is one way to think of the poor 1955 fit of automobile demand models.[4] Any explanation of all of the 1955 events from the demand side will need to be fairly fancy. However, it is clear that some fraction of the increase in 1955 auto quantity was due to demand factors.

Column 9 shows the accounting profits of the five largest operating automobile companies. The obvious, though wrong, inference is that there was a decrease in automobile competition in 1955. The technology of automobile manufacturing is characterized by large fixed costs: plant costs and product development costs are joint costs of production in many years. Standard accounting practice spreads these costs out smoothly over many years. As a result, there is no stable time-series relationship between accounting profit and price-cost margins in the economic sense. High unit sales years, like 1955, tend to be "profitable" in the accounting sense no matter what is going on in the economic sense.

Demand

Automobile purchasers typically buy one unit or none. The demand for automobiles is thus given by the number of buyers and not by the number bought by any hypothetical single consumer. Formally, we assume a continuum of potential buyers, differentiated by tastes. Each consumer chooses some automobile or decides to buy none. Aggregating the decisions of all consumers yields the demand functions for the automobile models. In this model, different consumers buy different autos because of differences in tastes. The heterogeneity in tastes are modelled in such a way as to yield a demand system for automobile models that is linear in prices. This requires strong assumptions. We assign every consumer a constant marginal rate of substitution between automobile quality and all other goods. Further, that marginal rate is distributed uniformly in the population of consumers. Each consumer, v, has tastes for automobile quality, x, and for money not spent on autos, $Y-P$;

(1) $$U(x, Y, v) = vx + Y - P \quad \text{if some auto is bought}$$

(2) $$U(x, Y, v) = v\gamma + Y - E \quad \text{otherwise}$$

[4] The quantitative extent to which standard auto demand models underpredict the 1955 expansion will be treated below.

The interpretation of γ and E in (2) will appear shortly. The interpretation of v is as willingness to pay for auto quality.

Consumers differ in their v, but there are equally many consumers with each v: v is distributed uniformly with density δ on $[0, V_{\max}]$.[5] Both δ and $V_{\max}$ are parameters for econometric estimation. Consider first the auto product selection part of the demand behavior of a consumer with utility (1). Let there be several products, each with price P and quality x. Then the consumer of type v will select that product j which minimizes $P_j - vx_j$. Aggregating this selection rule across consumers yields the demand for all of the products.

To aggregate individual demand behavior into product demand functions, first calculate the v of the consumer who is just indifferent between two products. Let products h and i have (p_i, x_i) and (p_h, x_h) with $x_i > x_h$. Then consumer v_{hi} is indifferent between h and i if and only if:

$$(3) \qquad P_i - x_i v_{hi} = P_h - x_h v_{hi}$$

Rearranging yields v_{hi} as a function of prices and qualities:

$$(4) \qquad v_{hi} = \frac{P_i - P_h}{x_i - x_h}$$

All consumers with $v > V_{ni}$ strictly prefer product i, all with lower v, product h.

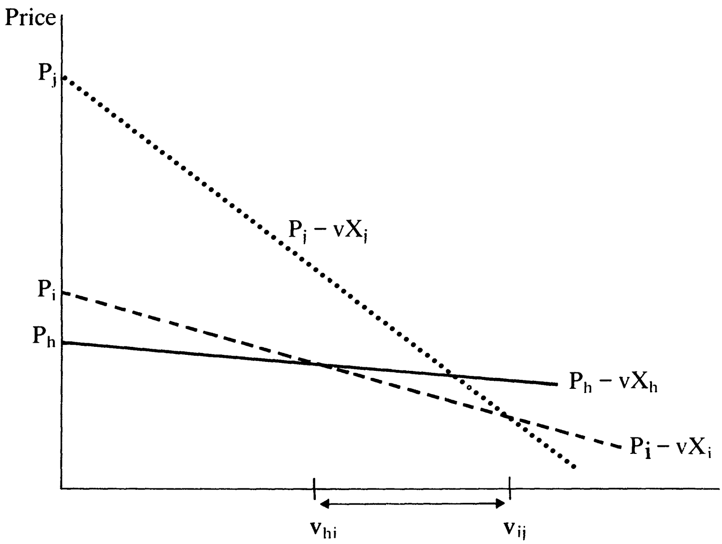

Figure 1

[5] The demand system is that of Prescott and Visscher [1977]. It has received considerable attention in the "Vertical Product Differentiation" literature, e.g. Shaked and Sutton [1983].

To find product i's demand function, let there be another product j with $x_j > x_i$. Calculate v_{ij} exactly as v_{hi}. Then product i is bought only by consumers in the interval $[v_{hi}, v_{ij}]$. Since the density of consumers is δ, the demand function is:

$$q_i = \delta[v_{ij} - v_{hi}] = \delta\left[\frac{(P_j - P_i)}{(x_j - x_i)} - \frac{(P_i - P_h)}{(x_i - x_h)}\right] \tag{5}$$

Note that the difference in qualities, $x_i - x_h$, is an indicator of how close substitutes the products are. The smaller the difference in qualities, the closer the cross-price demand derivative, $(\delta/(x_i - x_h))$ is to own-price demand derivative $-(\delta/(x_i - x_h) - \delta/(x_j - x_i))$ in absolute value. The products are perfect substitutes in the limit as x_i goes to x_h.

The selection of consumers into product market segments is illustrated in Figure 1. The three products have their prices on the vertical axis. The slope of the line through each product's price is (minus) its quality. Thus, the lines trace the "total price" of each product to consumers as a function of tastes, v. Product i is bought by these consumers in the marked interval, since it is there that i has the lowest total price. If product i's price were higher, or either of its neighbors lower, the market interval for i would shrink.[6]

That completes discussion of selection of products by those consumers who buy some auto. The other part of the demand functions, the decision whether to buy any auto, is now treated. The first assumption is that the person most valuing auto quality, $v_{\max}$, always buys some auto. Since the equilibrium $v_{\max}$ will always buy the highest-quality auto, x_n, the demand for the highest-quality auto is

$$q_n - \delta\left[v_{\max} - \frac{P_n - P_{n-1}}{x_n - x_{n-1}}\right] \tag{6}$$

To calculate the demand function for the lowest-quality good, consider the consumer's decision whether to buy any new auto. The rational consumer will compare the utility of the most-preferred auto to utility when no auto is bought. The decision to buy affects utility in three ways. First, there is less to spend on other goods. Second, there is the utility of having the automobile, vx. Third, preferences change from those given in (1) to those given in (2). The implication of (2), therefore, is that the consumer just indifferent between buying auto (P, x) has v equal to:

$$\frac{P - E}{x - \gamma} \tag{7}$$

[6] In fact, it is clear that the length of the interval is continuous in prices, even at those prices where that length goes to zero. It is also true that product i's demand function is concave across the point at which product $i+1$ is dominated out of the market. Thus price equilibrium always exists in "quality" product differentiation models like this one. In "location" models like that of Hotelling [1929], the continuity and concavity are absent, leading to potential nonexistence.

This has exactly the same form as (4), so that the demand function for the lowest-quality good is:

$$q_1 = \delta\left[\frac{P_2-P_1}{x_2-x_1}-\frac{P_1-E}{x_1-\gamma}\right] \tag{8}$$

It is exactly as if there were some other "product" below the lowest-quality product. This hypothetical "product" is most plausibly interpreted as a used car, as our data refer only to new-car purchases.

That completes specification of the demand side of the model. The demand function for products 1 to n are:

$$q_1 = \delta[v_{12}-vm](P_1,x_1) = \delta\left[\frac{P_2-P_1}{x_2-x_1}-\frac{P_1-E}{x_1-\gamma}\right] \tag{9}$$

$$q_i = \delta[v_{ij}-v_{hi}] = \delta\left[\frac{(P_j-P_i)}{(x_j-x_i)}-\frac{(P_i-P_h)}{(x_i-x_h)}\right] \tag{10}$$

$$q_n = \delta[vmu(P_n,x_n)-v_{nn-1}] = \delta\left[v_{\max}-\frac{P_n-P_{n-1}}{x_n-x_{n-1}}\right] \tag{11}$$

where E, γ, $v_{\max}$, and δ are the demand parameters to be estimated.

Costs and firm behavior

The cost of producing an automobile model is assumed to involve a fixed cost plus constant marginal costs at every quality level. The estimating equations come from the equilibrium conditions of the price-setting game among firms. The fixed costs are sunk at that stage; they do not affect decisions on the price-quantity margin, and so are ignored for the rest of the paper. What is of interest here is the relationship between marginal cost and product quality.

Formally, the cost function $C(x,q)$ has been restricted to the form:

$$C(x,q) = A(x)+mc(x)q \tag{12}$$

It is clear that $mc(\cdot)$ should be increasing, so that higher quality products are more expensive to manufacture. This avoids equilibria in which only the highest quality, yet cheapest product is produced. We also assume that $mc(\cdot)$ is convex, since this restriction implies that all products for which the fixed cost is sunk are sold in positive quantity.[7] A one-parameter functional form fulfilling these conditions is the exponential:

$$mc(t) = \mu e^t \tag{13}$$

where μ is a parameter to be estimated. The functional form is arbitrary, but

[7] Consumers trade off money and quality with a constant marginal rate of substitution. Convex costs, then, imply decreasing returns to expenditures on quality, an obvious condition to avoid degeneracies.

follows the success of hedonic models (c.f. Ohta and Griliches [1976]) in using a log linear form.

In order to calculate equilibrium prices and quantities from the vector of product qualities in the industry, only the form taken by the relations between firms remains to be described. Two assumptions about firm behavior are considered here. The collusive one has all firms setting prices to maximize the sum of all their profits, as if they were one monopolist. The competitive behavioral assumption has each firm setting the prices of its products to maximize its own profit, taking the prices of all other firms' products as given. These two solution concepts will be abbreviated C (Collusion) and B (Bertrand–Nash equilibrium with prices as strategic variables).

The profit function for a typical product is:

$$\pi_i = P_i q_i - mc(x_i) q_i - A(x_i) \tag{14}$$

Recall from (9)–(11) that the q_i are linear in P_i and in the prices of one or two neighboring products. The profit functions are therefore quadratic in prices, and the solution of any simultaneous profit-maximization problem will be linear in prices. We now construct the linear equations defining the equilibrium prices, showing their dependence on the behavioral assumptions.

The assumptions about firm behavior enter the determination of prices through the relations between neighboring products, since only neighbors have any interdependence on the demand side. Products more distant (than adjacent) in the quality scale have zero cross-price elasticities of demand. The neighboring products can either be cooperating (as all are under (C), or those of the same firm under (B)) or competing.

First consider a one-product firm which is not colluding with its neighbors. Since it is assumed to take their prices as given, it maximizes profit by setting the own-price derivative of the profit function to zero

$$\pi_i' = q_i + (P_i - mc(x_i)) \frac{\partial q_i}{\partial P_i} = 0 \tag{15}$$

If, instead, products i and $i+1$ are manufactured by the same firm or by different firms under (C), the first-order condition with respect to the i^{th} price is changed to:

$$\pi_i' = q_i + (P_i - mc(x_i)) \frac{\partial q_i}{\partial P_i} + (P_{i+1} - mc(x_{i+1})) \frac{\partial q_{i+1}}{\partial P_i} = 0 \tag{16}$$

The distinction is this: when the two products are cooperating, they maximize the sum of their profits. The extra term in (16) is the effect of i's price on $i+1$'s profit. If the market is characterized by a high degree of substitution (products closely spaced) this extra term will be large. Then the effect of changing hypotheses about competition will be substantial.

Of course, computation of equilibrium prices and quantities requires the specification and simultaneous solution of the first-order maximizing conditions for all products.

To specify these relations, let H be the matrix representing the state of cooperation, with elements defined by

$$H_{ij} = \begin{cases} 1 & \text{if products } i \text{ and } j \text{ are cooperating} \\ 0 & \text{otherwise.} \end{cases} \tag{17}$$

For example, in a hypothetical three-product industry where products 1 and 2 are produced by General Motors (GM), product 3 by Chrysler, the Bertrand H would be:

$$\begin{matrix} 1 & 1 & 0 \\ 1 & 1 & 0 \\ 0 & 0 & 1 \end{matrix} \tag{18}$$

since the first two products are presumed to cooperate, the third not. Under the collusive behavioral assumption, the H for the same industry would be:

$$\begin{matrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{matrix} \tag{19}$$

since all products are presumed to cooperate.

In this notation, the first-order condition for a typical product takes the form:

$$\begin{aligned} 0 = q_i + (P_i - mc(x_i))\frac{\partial q_i}{\partial p_i} + H_{ii+1}(P_{i+1} - mc(x_{i+1}))\frac{\partial q_{i+1}}{\partial P_i} \\ + H_{ii-1}(P_{i-1} - mc(x_{i-1}))\frac{\partial q_{i-1}}{\partial p_i} \end{aligned} \tag{20}$$

The effect of the behavioral assumptions on equilibrium prices can be seen in (20). An important determinant of $P_i - mc_i$ is the extent to which the single-product demand curve for i has slope $(q_i - (\partial q_i/\partial P_i)^{-1}$ in (20)). If the same firm produces the neighboring products, or if the firm is colluding with its neighbors, $P_i - mc_i$ is further increased. This follows from $(P_{i+1} - mc_{i+1})(\partial q_{i+1}/\partial P_i)$, P_i's impact on the neighbor's net revenue. It is easy to show that changing $H_{i,i+1}$ from zero to one for any i increases $P_k - mc_k$ for all k.

The equilibrium prices and quantities can be calculated by simultaneously solving the demand system (9)–(11) and all of the firm first-order conditions (20). The equilibrium price and quantity vectors are written:

$$\begin{aligned} p &= p^*(x, H, \gamma, V_{\max}, \delta, \mu) \\ q &= q^*(x, H, \gamma, V_{\max}, \delta, \mu) \end{aligned} \tag{21}$$

In the econometric specification described in the next section, the errors are additive in the reduced form.

To see the central intuition of the model, consider the example given in Figure 2. In the example, Firm One sells products 2, 4, and 5. Firm Two sells product 3. The prices of products 1 and 6 are held fixed—these products are sold by some third firm. In Figure 2(b), the equilibrium prices are shown under the assumption that Firms One and Two are *not* tacitly colluding. Note that the prices of products 2 and 3 are very near MC. This is because the products are nearly perfect substitutes and the solution concept is Nash in

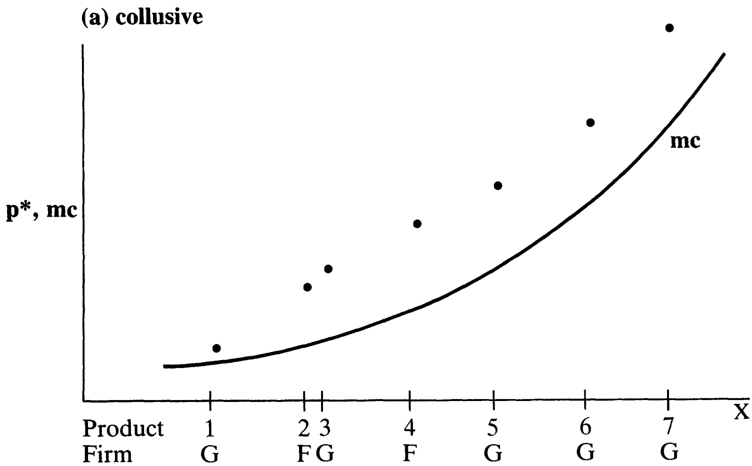

Figure 2(a)

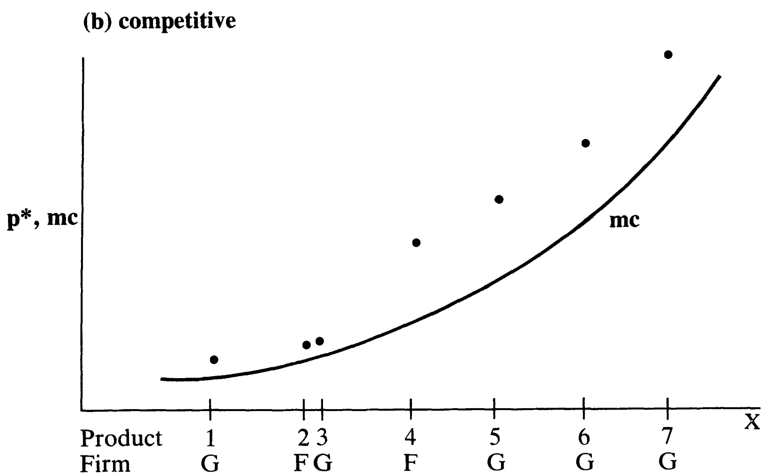

Figure 2(b)

Prices (Bertrand). In Figure 2(a), Firms One and Two are assumed to collude. The prices of products 2 and 3 are substantially above MC; that they are close substitutes is much less relevant when the firms maximize joint profits.

Products 4 and 5 change much less when the solution concept changes. Competition lowers their prices, of course, but it is distant rather than close competition. The intuition of the model is that product-space regions with many firms in them are quite different under competition and collusion. Product-space regions with only a few firms in them are similar under the two solution concepts, since there will be substantial market power even if firms compete.

In the mid-fifties automobile industry, the region like that around products 4 and 5 is the large-car end of the product spectrum. GM produced most of the cars sold in that segment. The region around products 1 and 2 is like the smaller-car segments; Ford, Chrysler, GM (and, to a lesser extent, the fringe and AMC are all present. Thus, for this industry, one should expect the methods developed in this section to have (statistical) power. In a product-differentiated industry where every producer had a full line, these methods might be less revealing. I shall return to this point in the concluding section.

II. ECONOMETRIC SPECIFICATION

Three main topics remain before estimation: proxies for quality, the data, and the error structure with its associated likelihood function.

Proxies for quality

The discussion of price equilibrium presumed that the quality of every product was known. In actuality, physical characteristics must be used as proxies. The interpretation of the proxy relationship comes from the hedonic price model of Rosen [1974]. Consumers are assumed to have preferences over the physical characteristics, z. Firms can produce automobiles at costs which depend on z. The proxy relationship is then interpreted as the expansion path of efficient (cost-minimizing) z's.

It is here arbitrarily assumed to take the square-root form:

$$x(c) = \sqrt{\beta_0 + \sum_j z_j \beta_j} \tag{22}$$

where β are parameters to be estimated. The interpretation of β is clouded by the fact that it contains information about both tastes and technology.

It is now possible to lay out the steps used in computing predicted prices and quantities from the parameters β, γ, μ, δ and $V_{\max}$ and the exogenous variables Z.

1. Each product is assigned a quality depending on the parameters β and its physical characteristics, z, using equation (22):

2. The products are ordered from highest to lowest, so that the product whose quality is i^{th} is assigned the index i:
3. The product qualities from step 1 and the rankings from step 2 plus the remaining parameters are used to solve (9)–(11) and (20) simultaneously for predicted values P^* and Q^*. The predicted values as a function of the parameters are then plugged into the likelihood function as described below.

Examination of (9) suggests that the demand for the lowest-quality good is overparameterized. The parameters E and γ were not easily distinguishable in data, so that the restriction $E = mc(\gamma)$ was imposed after some initial experimentation.

The data: A quantity aggregation problem

Data on prices, quantities and physical characteristics are nearly all from contemporary trade publications. A more precise version of their definition and collection is in Appendix A. Since the prime determinant of demand elasticities in the model is the difference in quality of automobile products, the definition of what constitutes a separate product is central to the data-handling part of this study. The model-naming conventions of the automakers are not useful in this regard. They vary widely across both time and firms.[8] The data used in this paper award an automobile model status as a separate product only if it is physically distinct from all others. This yields about 80–85 models each year, whereas the finest possible disaggregation might yield 140–150.

The level of disaggregation used in this paper is finer than the detail in which automobile manufacturers reported the quantities produced. For example, in the 1954 model year production data, Chrysler reports production for V-8 Desoto. But both Firedome and Fireflite models were sold with the V-8 engine. The solution to this problem is to aggregate predicted quantities up to the level of the data. In the example, the predicted quantities for the two V-8 models are summed; the difference between that sum and the reported quantity is the residual.

Since the coarseness of quantity aggregation varies over the sample, a problem of heteroskedasticity arises. It is assumed that the underlying quantity variance is $\sigma^2 q$ and that a predicted quantity formed as the sum of k products has variance $k\sigma^2 q$. If q_j is an observed quantity, we define I_j as the set of indices on the products making up q_j:

(23) $\quad i \in I_j$ if product i is to be aggregated to quantity j

$k_j = \text{card}(I_j)$ is the number of products so aggregated.

[8] "Independent" manufacturers sometimes doubled the number of model names offered for sale in the period with only trivial expansion in the set of physical products offered. This was usually a warning sign of impending exit.

Prices are list prices as of mid-April in the model year. The physical characteristics are those used in the Ohta and Griliches [1976] hedonic study: length, weight, horsepower, engine type and a body-type dummy.

The likelihood function

The predicted prices and quantities, P^* and Q^*, defined as functions of the parameters and the exogenous variables, z, are subject to additive, independent normal error. Quantity and price errors are independent. The price errors all have variance $\sigma^2 p$ while the quantity error j has variance $k_j \sigma^2 q$. Then the likelihood function is given by:

$$(24)\qquad \prod_{i=1}^{N_p} \frac{1}{\sqrt{2\pi^2 p}} \exp\left[-\frac{(P_i - P_i^*)^2}{2\sigma^2 p}\right]$$
$$* \prod_{j=1}^{N_q} \frac{1}{\sqrt{2\pi k_j \sigma^2 q}} \exp\left[-\frac{(q_j - \sum q^* k, kI_j)^2}{2k_j \sigma^2 q}\right]$$

where N_p and N_q are the price and quantity equation sample sizes. Since P^* and Q^* are computed only in terms of the parameters and the exogenous variables, this is fully a reduced-form error structure.

The likelihood function suffers a serious irregularity—it is not continuous in the parameters.[9]

All estimation was done by (numerical) maximum likelihood. The irregularities of the likelihood function could be expected to be troublesome here as well, since a discontinuous function cannot be concave.[10]

Other specifications estimated

In order to provide tests of the Collusive and Nash-competitive models, two other models are introduced.

The hedonic-price model has been given an interpretation as the perfectly competitive equilibrium of a continuously differentiated market by Rosen [1974]. Other authors have used the hedonic price approach in the presence of oligopoly, adding firm dummies as a proxy for "market power". We will estimate such a model, the loglinear price and quantity empirical hedonic model introduced by Cowling and Cubbin [1971] with UK automobile market data. This version of the hedonic model has predicted prices and

[9] Predicted prices are everywhere continuous, but there are discrete points in the parameter space where predicted quantities are discontinuous. The points of discontinuity are those β at which two products (including γ) are equal in quality. These are unlikely to be true parameter values, so that the limiting statistical inference goes through.

[10] One might expect numerical difficulties arising from local maxima. However, none were encountered. The points of discontinuity themselves are typically local minima because they involve extreme predicted quantities.

quantities in a recursive structure:

$$P_i^* = \exp\left[\alpha_0 + \sum_j \alpha_j z_{ij}\right] \tag{25}$$

and

$$q_j^* = \exp\left[\lambda_0 + \lambda_1(P_j - P_j^*)\right] \tag{26}$$

This model is endowed with precisely the same error and quantity aggregation structure as the oligopoly models. The hedonic model or something like it should hold if automobile list price data are set in some nonmaximizing way.

The justification for introducing the hedonic model for test purposes lies in its radical differences from the oligopoly models. Another way to test those models might be to specify an alternative that is very much like them. This is the justification for the "products" specification. This model follows exactly the theoretical development of the oligopoly models, except that each automobile product is treated as if it were manufactured by a separate firm. The matrix C for this specification is an identity matrix, since no two products are presumed to cooperate.

Neither the hedonic nor the "products" model is an appealing economic story of the automobile industry. But the test results of the next section show these two models to be extremely useful in rejecting false specifications among the oligopoly models.

III. EMPIRICAL RESULTS

This section presents likelihood-ratio (Cox) tests of each model against all the others. Discussion of the estimates and an analysis of the residual follows for those models not rejected in the test section.

Hypothesis tests

Although the models estimated here are not nested, the results of Cox [1961] and Pesaran and Deaton [1978] allow explicit hypothesis testing.[11] In Cox's framework, the hypothesis to be tested is confronted with the data and with an alternative, nonnested hypothesis. The likelihood ratio of the two hypotheses is the central statistic. Its mean and variance are computed under the assumption that the maintained hypothesis is true. If the difference of the likelihood ratio from its mean, divided by its standard deviation, is significantly different from zero, the maintained hypothesis is rejected. One attractive feature of the test statistic so obtained is that it is known to be asymptotically a standard normal under the maintained hypothesis, so that

[11] The Pesaran–Deaton nonlinear regression Cox-test formulae have been slightly altered to take account of the aggregation of quantities. See Appendix B.

TABLE III
COX TEST STATISTICS

Hypotheses	*C*	*N–C*	'*p*'	*H*
a—1954				
Collusion	—	0.8951	0.9464	−1.934
Nash-Competition	−2.325	—	−0.8878	−2.819
"Products"	−3.978	3.029	—	−1.604
Hedonic	−12.37	−10.94	−13.02	—
b—1955				
Collusion	—	−10.36	−9.884	−13.36
Nash-Competition	−1.594	—	1.260	0.6341
"Products"	−0.7598	−4.379	—	−1.527
Hedonic	−3.353	−8.221	−5.950	—
c—1956				
Collusion	—	1.227	0.8263	1.629
Nash-Competition	−2.426	—	−4.586	0.8314
"Products"	−3.153	0.9951	—	4.731
Hedonic	−5.437	−9.671	−11.58	—

one knows what a significant difference is. It is also possible for each of two models to be rejected against the other. This is the rationale for the introduction of the "products" and hedonic models. If the oligopoly models survive against these added alternatives, it will increase one's certainty that they are correct.

The test results are summarized in Table III. The nature of the Cox test is that one model, H_0, is assumed true and then contrasted with another model (H_1) and the data. The intuition of the tests is this: if the residuals under H_0 can be explained (to a statistically significant extent) by H_1, then H_0 is rejected. In Table III, the row stub gives the hypothesis being tested, the column header the alternative being used to test it. Values of the test statistic (asymptotically a standard normal) significantly different from zero lead to rejection.

The 1954 results show the hedonic model rejected against every other hypothesis. "Products" is rejected against each of the other two oligopoly models, though not against the hedonic model.[12] Nash-Equilibrium is rejected against the Collusive and Hedonic models. Only the Collusive model escapes rejection against any alternative.

The 1956 results clearly resemble those of 1954. No specification but Collusion escapes rejection, while Collusion is not rejected against any other model.

[12] Note that the Cox test is two tailed. "Products" is rejected in one instance because its likelihood is too large.

TABLE IV
PARAMETER ESTIMATES 1954–56, MAINTAINED SPECIFICATION

Parameters	*1954*[a]	*1955*[b]	*1956*[a]
Physical Characteristics			
Quality Proxies			
Constant	47.91	48.28	50.87
	(32.8)	(43.2)	(29.4)
Weight #/1000	0.3805	0.5946	0.5694
	(0.332)	(0.145)	(0.374)
Length "/1000	0.1819	0.1461	0.1507
	(0.128)	(0.059)	(0.146)
Horsepower/100	2.665	3.350	3.248
	(0.692)	(0.535)	(0.620)
Cylinders	−0.7387	−0.9375	−0.9639
	(0.205)	(0.115)	(0.186)
Hardtop Dummy	0.9445	0.4531	0.4311
	(0.379)	(0.312)	(0.401)
Demand/Supply			
μ—*Marginal Cost*	0.1753	0.1747	0.1880
	(0.024)	(0.020)	(0.035)
γ—*Lower Endpoint*	4.593	3.911	4.441
	(1.49)	(2.08)	(1.46)
$V_{\max}$—*Upper Endpoint*	$1.92E+7$	$2.41E+7$	$2.83E+7$
	$(8.44E+6)$	$(9.21E+6)$	$(7.98E+6)$
δ—*Taste Density*	0.4108	0.4024	0.4075
	(0.138)	(0.184)	(0.159)

Notes: Figures in parentheses are asymptotic standard errors.
[a] Estimated using the Collusion specification.
[b] Estimated using the Nash-Competition specification.

The 1955 estimates are very different. Collusion is rejected against all three alternatives, while Nash-Competition is not rejected against any. Despite this reversal, the remaining hypotheses are rejected in this year as in the other two.

Overall, the test statistics tell the story of a dramatic reversal in the 1955 automobile year. Supply side behavior was clearly much more competitive in 1955 than in the adjacent years.[13] The coincidence of these test results with the expansion in production that year is striking. It is important to emphasize that the tests results and the overall expansion are independent evidence. In the absence of cross-year restrictions, for example on the location of the automobile demand curve, there is no particular reason for the competitive model to be selected in the high quantity year. The reliability of the test

[13] The period 1954–56 is not entirely arbitrary. The Korean war price and quantity controls were lifted in February/March 1953. Foreign competition of any consequence begins with Volkswagen's entry in 1957. No labor-based work stoppages lasted more than ten days within the period.

results is also demonstrated by their robustness to the introduction of the two always-rejected specifications, the hedonic and "products".

The estimates

Table IV reports estimated parameters for those hypotheses not rejected in the tests of hypothesis. The 1954 and 1956 results come from the Collusion specification, the 1955 estimates from the Nash-competition specification. The similarity of the columns of Table IV is striking; the distinct features of the 1955 model year are captured by a change in behavioral assumption rather than by changes in the estimated parameters.

Tables V, which report parameter estimates for all years by specification, lack this consistency. When a single behavioral assumption is maintained throughout, the parameter estimates must provide the empirical explanation of 1955. In Table V(i), the results for the Collusive specification, the 1955 column departs from its neighbors. Note in particular that the 1955 estimate of μ is an order of magnitude larger, that for δ an order of magnitude smaller, than in the surrounding years. Further, length has a negative coefficient in 1955.

Table V(ii) which reports estimates from the Nash-Equilibrium specification, is similarly chaotic. 1954 shows the only negative value for the hardtop dummy estimated in any year for any specification. And the 1955 demand

TABLE V(i)
PARAMETER ESTIMATES 1954–56, COLLUSIVE SPECIFICATION

Parameters	*1954*	*1955*	*1956*
Constant	47.91	−23.37	50.87
	(32.8)	(24.5)	(29.4)
Weight	0.3805	0.0103	0.5694
	(0.332)	($5.43E-2$)	(0.374)
Length	0.1819	$-2.88E-3$	0.1507
	(0.128)	(0.102)	(0.146)
Horsepower	2.665	0.1165	3.248
	(0.692)	(0.106)	(0.620)
Cylinders	−0.7387	−1.309	−0.9639
	(0.205)	(1.52)	(0.186)
Hardtop	0.9445	1.468	0.4311
	(0.379)	(1.08)	(0.401)
μ	0.1753	1.344	0.1880
	(0.024)	(0.151)	(0.035)
γ	4.593	1.604	4.441
	(1.49)	(4.83)	(1.46)
V_{max}	$1.92E+7$	$1.46E+8$	$2.83E+7$
	($8.44E+6$)	($6.74E+6$)	($7.98E+6$)
δ	0.4108	$5.75E-2$	0.4075
	(0.138)	($8.28E-2$)	(0.159)

Note: Figures in parentheses are asymptotic standard errors.

TABLE V(ii)
PARAMETER ESTIMATES 1954–56, BERTRAND SPECIFICATION

Parameters	*1954*	*1955*	*1956*
Constant	31.64	48.28	33.23
	(29.9)	(43.2)	(17.8)
Weight	0.9311	0.5946	$6.23E-3$
	(0.210)	(0.145)	$(8.73E-4)$
Length	0.1474	0.1461	0.1605
	(0.038)	(0.059)	(0.149)
Horsepower	4.962	3.350	$2.972E-2$
	(0.676)	(0.535)	$(1.47E-2)$
Cylinders	−0.8846	−0.9375	−0.9078
	(0.194)	(0.115)	(0.256)
Hardtop	−0.2474	0.4531	0.5282
	(0.464)	(0.312)	(0.249)
μ	0.2518	0.1747	0.2902
	(0.074)	(0.312)	(0.249)
γ	6.352	3.911	1.204
	(3.54)	(2.08)	(3.19)
V_{max}	$9.81E+5$	$2.41E+7$	$1.03E+6$
	$(8.78E+6)$	$(9.21E+6)$	$(8.90E+6)$
δ	5.04	0.4024	7.334
	(1.21)	(0.184)	(2.46)

Note: Figures in parentheses are asymptotic standard errors.

TABLE V(iii)
PARAMETER ESTIMATES 1954–56, HEDONIC SPECIFICATION

Price Equation	*1954*	*1955*	*1956*
Constant	5.294	4.469	5.239
	(2.52)	(0.230)	(0.371)
Weight	0.6117	0.4098	0.6537
	(0.093)	(0.068)	(0.023)
Horsepower	−0.7760	−0.3891	−0.8121
	(0.574)	(0.605)	(0.125)
Cylinder	0.0417	0.0442	0.0976
	(0.086)	(0.082)	(0.087)
Hardtop	2.438	3.171	2.381
	(0.224)	(0.379)	(0.257)
GM Dummy	−0.445	−0.0563	−0.0783
	(0.024)	(0.024)	(0.024)
Ford Dummy	−0.0191	0.7706	−0.0435
	(0.044)	(5.31)	(0.045)
Quantity Equation	*1954*	*1955*	*1956*
Constant	6.386	6.814	6.332
	(2.96)	(3.58)	(2.11)
Price	−3.742	−1.312	−3.322
	(0.640)	(0.787)	(0.715)

Note: Figures in parentheses are asymptotic standard errors.

parameters show tastes distributed at one tenth the density over ten times the range in the population as in the surrounding years. Table IV, which is after all constructed from these two tables, tells a much more consistent story of the underlying market than they. Indeed, no set of maintained hypotheses other than that left unrejected by the data, no other conceivable Table, could tell that consistent story. It is change of behavioral assumption, not change of parameter values, that provides a reasonable empirical explanation of 1955.

The parameter estimates in Table IV can be conveniently discussed in two groups. First are the quality-proxy parameters, β. In sign and absolute value, they are what one would expect from a hedonic regression. The one counter-intuitive sign, the negative "cylinders" coefficient, is also familiar from hedonic analyses. The econometric interpretation is that "horsepower" and "cylinders" are highly collinear. The economic interpretation is that the "cylinders" variable captures the fall in the cost of horsepower after the introduction of the V-8 engine.

The rest of the parameters require more discussion. The two central demand parameters, $V_{\max}$ and δ, tell a story of quite diverse tastes for automobile quality. Recall that δ is the density of the distribution of tastes in the population, $V_{\max}$ its upper limit. The eight million 1955 buyers then had v distributed over the interval $(4.24E+6, 2.4E+7)$. In other words, the distribution of tastes among buyers was 20 million wide and 0.4 deep (with 20 million times 0.4 giving the eight million buyers). This finding may be an artifact of the constant density assumption. The other demand parameter, γ, represents the quality of the hypothetical used car into which new-car nonbuyers substitute. It is estimated to be around 4 in each year; the lowest quality auto has quality just around 9. Thus, new and used cars are not very close substitutes. The final parameter, μ, serves only to correct the units of quality to those of money in the marginal-cost relation.

A simple calculation can clarify the role of shifts in demand versus changes in form behavior in explaining the 1955 expansion. What prices and quantities would have been observed if collusion had reigned in 1955 as well? To answer this question, we calculate equilibrium predicted values using the 1955 parameter estimates (which were estimated under the Bertrand specification) and the collusive solution concept. This calculation leads to an *increase* of 1955 prices over each of the surrounding years—about one-half of one percent over the average of 1954 and 1956. It also leads to predicted 1955 unit sales of 7.1 million units—25.5%, not 40.4%, higher than the 1954/56 average. One way to interpret this is in light of the demand for autos literature. The largest residual in Chow's [1960] demand system comes in the 1955 data. It is +0.6 million units. This is clearly comparable to the change implied by the supply side of 0.8 (7.9 − 7.1) million units.

One surprise is that the 1955 purchases do not seem to have depressed 1956 demand. In Table IV, both δ and $V_{\max}$ are greater in 1956 than in 1955, but the increases are not great. More significant is the high value of γ in 1956. This

TABLE V(iv)
PARAMETER ESTIMATES 1954–56, "PRODUCTS" SPECIFICATION

Parameters	*1954*	*1955*	*1956*
Constant	57.95	17.32	46.06
	(26.1)	(27.6)	(26.6)
Weight	$5.478E-3$	$7.98E-3$	$6.221E-3$
	$(3.44E-2)$	$(4.63E-2)$	$(8.62E-3)$
Length	0.1731	0.8984	0.1926
	(0.529)	(0.576)	(0.390)
Horsepower	0.0520	−1.003	0.0287
	(0.056)	(0.089)	(0.076)
Cylinders	−0.5267	0.3799	−0.9456
	(0.894)	(0.699)	(0.587)
Hardtop	0.2811	0.5656	0.4075
	(0.511)	(0.534)	(0.687)
μ	0.1334	0.1507	0.1748
	(0.415)	(0.224)	(0.245)
γ	6.894	1.482	1.270
	(2.86)	(4.48)	(2.99)
$V_{\max}$	$4.21E+7$	$1.61E+8$	$1.05E+6$
	$(8.57E+6)$	$(8.38E+6)$	$(8.71E+6)$
δ	0.9648	$5.01E-2$	7.174
	(0.552)	$(8.09E-2)$	(2.27)

Note: Figures in parentheses are asymptotic standard errors.

indicates considerable competition from the used-car market. On the other hand, 1954 and 1956 have very similar demand parameters. Thus, it is difficult to argue that the 1956 estimates reflect the previous year's high quantity sold.

The residuals and some simple generalizations

Table VI gives part of the intuition behind the formal test results. The reversal between the Collusion/Bertrand models shows up here as a general reversal

TABLE VI
PRICE AND QUANTITY,* EQUATION R^2

	1954		*1955*		*1956*	
Model	*P*	*q*	*P*	*q*	*P*	*q*
Collusion	0.94	0.62	0.92	0.58	0.96	0.61
Bertrand	0.91	0.62	0.96	0.64	0.93	0.62
"Products"	0.90	0.62	0.88	0.59	0.92	0.61
Hedonic	0.89	0.71	0.88	0.73	0.88	0.71

* Quantity equation R^2 is defined as a fraction of explained variance because of the heteroskedasticity problem. That is, $R_q^2 = (s_q^2 - \hat{\sigma}_q^2)/s_q^2$, where s_q^2 is the second raw moment of the quantity data, estimated under the same heteroskedastic variance structure as used in the econometric models.

TABLE VII
BIG THREE VS. ALL OTHERS AVERAGE RESIDUALS

	1954[a]	*1955*[b]	*1956*[a]
a—Prices			
GM	20.92	28.80	21.48
Ford	−12.33	−6.28	−11.02
Chrysler	−13.16	−9.33	−17.19
b—Quantities			
GM	−99.6	−82.86	−68.73
Ford	60.2	22.97	19.06
Chrysler	96.89	64.47	11.94

Notes: Figures are: average residual for firm named minus average for all other firms (including other two big-three firms). Price figures have dollar units; quantity figures, number of cars.
[a] Estimated from Collusive specification.
[b] Estimated from Nash-Competitive specification.

in R^2. In each year, the model not rejected explains more variance in both equations. A somewhat more surprising result is the consistently better fit of the hedonic model in the quantity equation. Since this does not lead to rejection of the structural oligopoly models against the hedonic alternative, I conclude that the price equation is providing most of the power for the hypothesis tests.[14]

Table VII compares the average residuals (from the unrejected specification) for each of the big three automakers to residuals for all other firms. Since "all other firms" for Ford and Chrysler includes GM, I conclude that the clearest message from this table is about GM. The oligopoly models consistently overpredict GM prices by \$30 (out of the \$1500 price of a typical car) and underpredict GM sales by 100 units (out of typical sales of around 60 000). These figures are not large enough to be alarming, but they do suggest that GM enjoyed either a cost or quality advantage over other producers. Two slightly more general specifications were estimated (for each oligopoly model) as a result. In one, a GM dummy was added to z, to capture superior quality. In the other, GM got a separate marginal cost parameter μ. Neither β_{GM} nor μ_{GM} was significant in any unrejected hypothesis. No Cox-test result was reversed in the broader specifications. Inclusion of either GM-specific parameter does make Table VII look much more like zeros, however.

The economic hypotheses tested in the last section depend in a crucial way on the assignment of imputed qualities, x_i, to each auto i. The tests depend crucially on which products are neighboring. Small errors in the prediction of x_i, for example, could change the *ordering* of the products, and thus change

[14] The problem here is that the models introduced in this paper have no constant in the quantity equation. See (9)–(11). For prices, mc explains much of the cross-section variance, so R^2 would be high even if not much of the markup were being explained.

the extent to which products produced by the same firm are neighboring or not. This can clearly have a large effect on the predicted values.[15] This problem can be minimized with a simple generalization. Following Bresnahan [1981], the quality-proxy relationship is rewritten as observed with error

$$x(z) = \sqrt{\beta_0 + \varepsilon_j \beta_j Z_j} + \varepsilon_x$$

Since x is not (directly) observable, ε_x must be integrated out of the likelihood function. This has an imporant effect on the nature of substitution across products. When ε_x has zero variance, each product is predicted to be a substitute for only two others. As the variance of ε_x increases, there is greater and greater probability of demand-side interaction with less similar products. Thus, this expansion of the specification "smears" the demand equations, significantly reducing the importance of very similar products. Unfortunately, I do not know how to construct Cox tests for this broader specification. The likelihoods of the broader specification, however, show that the Bertrand model fits best in 1955 and the Collusive model in the other years. There is, therefore, no reason to believe that the test results are an artifact of the quality-proxy.

The third simple generalization is designed to test a glaring shortcoming of the specification—that automobiles are treated as a flow good rather than a durable. This is accomplished by expanding the specification to

$$P_i = P_i^*(\cdot) + \lambda S_i + \varepsilon_p$$

and

$$q_i = q_i^*(\cdot) + \theta S_i + \varepsilon_q$$

S_i is defined as the stock of used cars "like" model i. Here "like" means within ten percent in weight, and used cars are assumed to depreciate at 15 percent per year. This is *ad hoc*, but should show something of the results are an artifact of the nondurability assumption. In fact, both λ and θ differ significantly from zero, but the Cox test results of Table III are unaltered.[16]

The primary results of this paper have been subjected to two kinds of tests: the simple increases in parameterization in this section and the tests against the hedonic and "products" specification in the last. I conclude first that the highly structured oligopoly models estimated here do not tell all of the story the data have to tell. I conclude second that the conclusions about firm behavior appear nonetheless to be robust.

IV. CONCLUSION

The 1955 auto model year had three anomalous features: price fell during a macroeconomic expansion, quantity increased well out of proportion to

[15] Professor Robert Masson made this argument, which is clearly a possible problem.
[16] The results were rerun only for the collusive and Bertrand specifications.

experience, and the share of the basic transportation segment in total auto sales increased. The hypothesis that tacit collusion among the automakers broke down in 1955 explains these anomalies. Like any supply-shift story, it explains the aggregate quantity and price-index movements. It rationalizes the segment shift because of differences in the nature of competitive interaction across auto market segments. The effect of increased competition on prices and quantities should have been largest in the small-car segment, where every company's products have close substitutes sold by competitors. The price war hypothesis thus explains the aggregate data as well as standing up well in econometric tests. These tests are based on the fine structure of automobile prices and quantities in cross-section.

There are two classes of methods available for empirical studies of market power. One class looks for explicit indicators of market power, for example price-cost margins. The difficulty here lies in the use of accounting data as a proxy for economic variables. The issues raised in section I about the allocation of capital costs over time strongly suggest that these methods are unsuitable for studies of single industries. A second class of method specifies and estimates structural demand and supply equations. In the presence of market power, the supply equation includes a term for the demand elasticity. Econometric detection of market power then depends on estimation of this term. This was the kind of method used in this paper. In a product-differentiated industry like automobiles, a crucial determinant of the demand elasticities is the "distance" between products in quality space. Under non-cooperative oligopoly solution concepts, such as the Bertrand model used here, it matters a great deal whether the same firm or different ones produce close substitutes. In the former case, the marginal revenue term in the imperfectly competitive supply equation is substantially larger. This distinction disappears under collusion. Thus by focussing on the structural supply equation, the econometric methods used here can discriminate between competition and collusion.

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APPENDIX A

Data sources and handling

In this paper's empirical work, the economic variables price, quantity and product characteristics are observed as list price, model-year production and engineering specifications. One source of these data is contemporary trade publications: *Ward's*, *Automotive Industries*, and *Automotive News*. The other source is Heasley [1977], based on interviews with automobile executives made between 1972 and 1974.

In general, two sources were available for every number in the data. These and precise descriptions of data provenance follow; this paragraph gives a thumbnail sketch. (1) Model specifications and list price data were copied, except for minor error checking. (2) Model-year production figures were used when reported. Otherwise the figures were constructed from monthly production data and the dates of the model year. (3) The decision as to what constitutes a separate model was independent of maker's model naming conventions. Physical distinctness led to classification as different models.

List prices are reported in tables in all three trade journals and in the Company Pages of *Ward's*. The *Ward's* and *Automotive News* tables failed to match on about two percent of all prices; recourse to the other two sources led to a three-way match in every case. No "dealer discount" correction was made since the discount was constant across models before 1959. The prices used are Ohta and Griliches [1976] "PA" Options are excluded, except heaters where the information is available. Power steering and power brakes are included only if standard.

Model specifications are available in all three trade journals in tables. The *Ward's-Automotive Industries* check yielded a nonmatch rate of over five percent. *Automotive News* resolved all of the nonmatches but one, which could be found in a contemporary brochure. The characteristics were:

Length: Bumper to bumper length in thousands of inches;
Weight: "Curb Weight", full trim included, but unloaded in thousands of pounds;
Horsepower: Advance maximum brake horsepower, in hundreds;
Cylinders: Number;

and

Hardtop: A body type dummy, one for hardtop models.

Model-year production is reported in incomplete tables in *Automotive-News*, *Ward's*, and Heasley [1977] and, also incompletely, in the Company Pages of *Ward's*. Monthly production data are also available, somewhat less incompletely, in all three trade journals. The match rate for the following procedure was 100 percent. Incomplete model year tables were filled in using the monthly data. Although model years rarely begin on the first of the month, the model changeover was always revealed (by the work-stoppage tables) to have encompassed the first. This permitted exact calculation. Heasley [1977] figures were usually the second source to confirm the constructed data, since the trade journal tables were usually all incomplete in exactly the same way.

Production data, rather than sales or registrations, have the advantage that they can be tied very precisely to the model year. Thus it is clear what physical product was sold in these data. On the other side, production data do not clearly correspond to a market definition. In particular, neither fleet sales nor end of model year bargains can be adequately treated.

The empirical definition of an automobile model is crucial to this study. Models were construed distinct in the data if they: (1) were of different makes (Pontiac and Chevrolet are different makes for this purpose even though both are GM manufactured); (2) had different engines, frames or body types. Only the hardtop and 4-door sedan (replaced by 2-door for those models with no 4-door) body types are included; or (3) differed in weight or length by over one percent.

APPENDIX B

Cox test statistics

The models estimated in this paper differ from the general regression models of Pesaran and Deaton [1978] in two ways. First, the price-quantity error covariance is here constrained to be zero, and second, there has been aggregation in the quantity equation. These two differences do not alter the nature of the test statistics in any important way, but it is necessary to allow for them in the computational formulae.

First define

(B.1) $s^2jp \equiv$ estimated price variance under H_j

and

(B.2) $s^2jq \equiv$ estimated quantity variance under H_j

Now consider this phony-data regression. Take the predicted values from H_0. Use these as if they were data in specification H_1. Call the estimated variances from the regression ϕ^2p and ϕ^2q. Now define:

(B.3) $s^210p \equiv s^20p+\phi^2p$

(B.4) $s^210q \equiv s^20p+\phi^2q$

Then the numerator of the Cox test statistic, which is the difference between the H_0H_1 log-likelihood ratio and its expected value when H_0 is true, is given by:

$$T_0 = \frac{Np}{2}\log\left[\frac{s^21p}{s^210p}\right]+\frac{Nq}{2}\log\left[\frac{s^21q}{s^210q}\right] \tag{B.5}$$

where Np and Nq are the price and quantity equation sample sizes.

The denominator of the test statistic is the (asymptotic) variance to T_0. To compute it requires another regression. Take the residuals from the phony-data regression above and regress them (linearly) on the derivatives of the predicted values with respect to the parameters under H_0. Call the estimated variances in that regression ϕp and ϕq. Then:

$$V_0(T_0) = Np\phi p\left[\frac{s^20p}{s^410p}\right]+Nq\phi q\left[\frac{s^20q}{s^410q}\right] \tag{B.6}$$

The ratio of $T_0/V(T_0)$ is asymptotically a standard normal if H_0 is true. As with all asymptotic statistics in this paper, that asymptotic normality is unproven, since the likelihood function does not meet the regularity conditions for nonlinear regression. The hedonic-price model does not come under this caveat. Its rejection in this paper is statistically quite clean.

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