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New car sales and used car stocks: a model of the automobile market

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This article develops a short-run general equilibrium model of the automobile market by combining a discrete choice model of consumer automobile demand with simple models of new automobile production and used vehicle scrappage. The theoretical model allows an unlimited degree of heterogeneity of both consumers and automobiles, with equilibrium defined as aggregate demand equal to supply for every vehicle type. Econometric estimates of the scrappage and demand functions are then used to create a simulation model of the automobile market, which is used to provide forecasts of automobile sales, stocks, and scrappage for the 1978–1990 period.

1. Introduction

■ Automobile market behavior is of significant interest because of the substantial impacts of automobile production and use on a variety of public policy concerns including trade flows, business cycles, energy demand, and air pollution. Consequently, many government regulatory programs have attempted to alter automobile sales and use patterns. Although recent public attention has been focused on governmental attempts to increase sales of domestic vehicles via "voluntary" export restrictions, the government has been an active participant in the automobile market through direct product quality regulation for many years. During the past quarter century, the federal government has intervened in the automobile market to correct perceived market failures through a variety of regulations designed to increase vehicle safety while reducing air pollution and energy consumption. These regulatory policies alter some characteristics of newly produced vehicles (e.g., miles per gallon), thereby gradually achieving their objective (improved fuel efficiency) as old vehicles are retired and replaced by new ones. Frequently these regulations appear to conflict, with safer and cleaner cars being less energy efficient. All of these policies work in similar ways on the automobile market in that they modify the attributes (including prices) of the new vehicles available to consumers, thereby leading to different consumer purchases of new vehicles.

The complexity of the automobile market makes it difficult to evaluate the effects of these policies, especially in the short run. Automobiles are highly differentiated durable goods with variable lifetimes. If an "improvement" (e.g., fuel efficiency) is mandated in the offerings of new cars at a sufficiently high cost, it will induce a demand shift away from new

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vehicles and cause existing vehicles to be more highly valued and longer lived. This may cause the fuel efficiency of the vehicle stock to fall in the short run if older cars are sufficiently less efficient than new cars. Empirical estimates of market response are needed to evaluate the effectiveness of regulations.

Economists and planners have developed many models of automobile supply and demand.[1] One of the most promising approaches to modelling automobile demand uses discrete choice models of household vehicle demand. This is appealing because it allows for an almost unlimited degree of product differentiation. This article develops a microsimulation model of the automobile market from a discrete choice model of household automobile demand. This simulation model combines a household-level model of automobile quantity and type choice with a simple supply model for new vehicles and a scrappage model for used vehicles in a short-run general equilibrium framework. In the short-run general equilibrium context, prices are adjusted so that supply equals demand for each new and used vehicle type during each period.

The article is organized as follows. Section 2 develops theoretical models of automobile supply, demand, and scrappage. Section 3 presents empirical estimates of the demand and scrappage models and discusses data and estimation methods for the econometric models. Section 4 presents the simulation system and discusses the procedures used to calculate equilibrium prices. Empirical forecasts of automobile stocks, sales, fleet miles per gallon, and scrappage are then discussed for a base-case scenario for the 1978–1990 period. Several policy scenarios are also presented, which illustrate market response to increased prices for new domestic or imported vehicles.

2. Automobile market model

■ The automobile market is represented as a sequence of market periods of finite and equal length. For simplicity, we assume that the vehicle stock available during any period can be represented by a finite number of vehicle "types." Each vehicle type is completely described by a package of physical attributes (e.g., size, miles per gallon), and all cars of a given type are assumed to be identical.

Three sectors are represented in the model: new vehicle manufacturing, consumer demand, and used vehicle scrappage. During each period consumers demand vehicles and a *numeraire* composite commodity, while manufacturers supply new vehicles in exchange for the composite commodity. Consumers purchase new vehicles from manufacturers, and trade used vehicles among themselves and with the scrap sector, which buys old "scrapped" vehicles in exchange for the *numeraire* good. Prices of all vehicles adjust until a market-clearing equilibrium is reached for every vehicle type, with all transactions during the period occurring instantaneously at the market-clearing prices.

The vehicles, both new and used, purchased by consumers in one period then become the stock of used vehicles available in the next period. The dynamics of the model are provided by the carryover of the vehicle fleet between periods and the multiperiod behavior of producers and consumers.

More formally, let there be T time periods indexed $t = 1, \ldots, T$. At every time t there are N vehicle types available, where vehicle types are indexed by class $j = 1, \ldots, J$ and age $i = 1, \ldots, I$. There also exists a single *numeraire* commodity, Y, which is the $N + 1$st good.

We then have the following definitions:

P^t = the vector of current and expected future prices (in terms of *numeraire*);[2]
X^t = a matrix of automobile characteristics;
Z^t = a matrix of consumer characteristics;

[1] See Train (1979) or Tardiff (1980) for literature reviews.
[2] Throughout this article all prices are assumed to be real (in terms of *numeraire*) unless otherwise noted.

$R^t_{ij}(P^t, X^t)$ = the number of vehicles of age i and class j being scrapped (or retired) during period t;
$D^t_{ij}(P^t, X^t, Z^t)$ = the consumer demand for vehicle ij in period t;
$S^t_{ij}(P^t, X^t)$ = the production quantity of vehicle ij in period t;
Q^t_{ij} = the existing stock of vehicle ij in period t;
$Y^S_{ij}(P^t, X^t)$ = the amount of the *numeraire* good used in producing S^t_{ij};
$Y^D(P^t, Z^t)$ = the demand for *numeraire* composite good by consumers;
$Y^R_{ij}(X^t)$ = the amount of the composite commodity produced by the scrappage of quantity R^t_{ij}.

During each period t, equilibrium is defined as market clearing in all markets:

$$S^t_{ij}(P^t, X^t) + Q^t_{ij} = R^t_{ij}(P^t, X^t) + D^t_{ij}(P^t, X^t, Z^t) \qquad \text{for all } ij, \tag{1}$$

where

$$S^t_{ij} = 0, \qquad i \neq 1$$

$$Q^t_{1j} = 0, \qquad \text{all } j,$$

and

$$Y^D(P^t, Z^t) + \sum_{ij} Y^S_{ij}(P^t, X^t) = \sum_{ij} Y^R_{ij}(X^t) + \bar{Y}^t, \tag{2}$$

where $\bar{Y}^t$ is the exogenous endowment of the composite commodity in period t.

The model dynamics are provided implicitly by the functions $S^t(\cdot)$, $R^t(\cdot)$, and $D^t(\cdot)$ and by the accounting identity for the vehicle stock,

$$Q^{t+1}_{ij} = D^t_{ij}(P^t, X^t, Z^t), \qquad \text{all } ij, \tag{3}$$

stating that the stock of a particular type in the next period is the current aggregate consumer holdings of that type.

□ **New vehicle production.** Automobile manufacturing is characterized by few producers and a wide variety of product differentiation. To avoid difficult issues of oligopolistic behavior, this analysis assumes simple supply rules for new car manufacturers on the basis of a simple competitive model.

Following the oligopoly models of Bresnahan (1981), assume that the manufacturer's decisions about new car supply can be divided into two components: (1) a longer-run decision about which product types to make and (2) a short-run pricing decision. For the purposes of this model, we assume that manufacturers make only pricing decisions during each market period with vehicle designs being fixed exogenously. Although vehicle designs can be expected to adjust to market forces over time, this process is beyond the scope of this article and will not be addressed here.

During each market period, each manufacturer produces a given set of vehicle designs and can only change prices and quantities in the short run. As a further simplification, we assume that each product has a well-defined short-run supply schedule that is a function of only its own price. The supply schedule for product n, $S_n(P_n)$, can be derived from an underlying production technology by using some restrictive assumptions about firm behavior.[3]

Supply schedules are assumed to be continuous and nondecreasing in prices. To ensure that the supply schedule is well behaved for all positive prices, we assume a lower limiting value of 0 and a positive upper limit. Note that supply behavior can range from constant returns to scale (fixed price) to inelastic (fixed quantity) over intermediate price ranges.

The production process for each product type is then completely described by three functions giving inputs, outputs, and profits as functions of prices:

[3] See Berkovec (1983) for more detail.

$$\left.\begin{array}{ll} S_n(P_n) \geq 0 & \text{output quantity of } n \\ Y_n^S(P_n, X_n) & \text{input used to produce } S_n(P_n) \\ \pi_n(P_n) = P_n S_n(P_n) - Y_n^S(P_n, X_n) \geq 0 & \text{profits.} \end{array}\right\} \tag{4}$$

If profits are positive, they are redistributed to consumers in some specified manner. In each period revenues will always cover short-run variable costs.

□ **Vehicle scrappage.** The retirement of a vehicle from the active fleet occurs when a vehicle is scrapped and used for scrap metal or spare parts. Automobile scrappage is an economic decision: scrappage occurs when a vehicle has more value as scrap than as a working vehicle. Households vary in their valuations of vehicles, but vehicles will be retained in the vehicle stock unless the price that can be obtained in the used car market is less than the car's value as scrap.

The scrappage model used in this analysis is based on the model of Manski and Goldin (1982). Each vehicle is assumed to have a probability of failing during each period. Once a failure occurs, there is a random repair cost necessary to restore the failed vehicle to working condition. A vehicle will be repaired only if its required repair cost is less than its value as a working vehicle. Scrappage occurs if

$$P_n - \delta_n < C_i,$$

where

C_i = the realized repair cost of vehicle i of type n;
δ_n = the scrap value of a vehicle of type n;
P_n = the price of a vehicle of type n (in good condition).

Thus, the probability of scrappage's occurring is

$$\Pr(\mathit{Scrap}\ i) = \Phi_n(1 - F_n(P_n - \delta_n)), \tag{5}$$

where

Φ_n = the failure probability of a vehicle of type n;
F_n = the cumulative distribution of repair costs.

Using specific functional forms for Φ and F, Manski and Goldin (1982) derive a log-linear relationship between scrappage probabilities and vehicle prices (P) and characteristics (X):

$$\Pr(\mathit{Scrap}\ n | X_n, P_n\beta) = \exp[\beta_0 + X_n\beta_1 - \beta_2 P_n + \beta_3 P_n^2 + \mu_n], \tag{6}$$

where β's are unknown parameters and μ_n is a random error.[4]

The scrappage market can be envisioned as another consumer sector, which demands vehicles on the basis of prices and attributes, but, unlike other consumers, the scrappage sector does not return vehicles to the market in later periods. The scrappage sector has nicely behaved "demand" functions for all products, which depend solely on own prices. If prices are well above scrappage values δ, then the demand for scrapped vehicles of type n, $R_n(P_n)$, is given by:

$$R_n(P_n) = \Pr(\mathit{Scrap}\ n) Q_n, \tag{7}$$

where

$\Pr(\mathit{Scrap}\ n)$ = probability of scrappage (scrappage rate);
Q_n = total stock of n.

[4] The quadratic form of prices is an artifact of normality assumptions about error terms. The function should remain decreasing in prices throughout the relevant range for consistency with the derivation of the model. See Berkovec (1983) or Manski and Goldin (1982) for details.

The theoretical basis for the scrappage model suggests that as prices approach the scrappage price, δ, an increasing fraction of vehicles are scrapped as smaller failures result in scrappage. In the limit as P_n approaches δ, all vehicles of type n will be scrapped as even normal routine maintenance is not worthwhile. The scrappage function, $R_n(P_n)$ as defined by (7), does not necessarily perform well as prices approach scrap values. To correct this and to ensure that prices remain positive in equilibrium, we shall impose the condition $R_n(\delta_n) = Q_n$.[5]

□ **Automobile demand.** The consumer demand functions that are the core of this model are based on discrete choice consumer theory. During each market period every consumer is assumed to choose the optimal vehicle package from among those available. The vehicle bundle is then held until the beginning of the next period when the consumer's vehicle holdings can again be altered. Dynamic problems are minimized by assuming that transaction costs are minimal and that there are no information discrepancies between agents. Consumers then act as if maximizing a single-period utility function during each period.

For our purposes, the consumer's decisionmaking unit is assumed to be a household and the vehicle choice decision includes both what number to own and which types to own. Each household then chooses the vehicle bundle m from the set M that maximizes a conditional indirect utility function $V(X_m, Z_s)$, where X_m are the characteristics of vehicle bundle m and Z_s is a vector of characteristics of household s. The set of options $M = [\phi, N_1, N_2, \ldots, N_l]$ contains all possible vehicle bundles including the null option ϕ and all possible combinations of l vehicles, N_l, given N distinct vehicle types.

V is assumed to consist of a deterministic component and a stochastic component:

$$V(X_m, Z_s) = \bar{V}(X_m, Z_s) + \epsilon_{sm}, \tag{8}$$

with ϵ_{sm} an unobservable random error.

Now define $H(m|Z_s, M)$ as the probability of observing choice m from set M, given observable household characteristics Z_s:

$$H(m|Z_s, M) = \Pr[\bar{V}(Z_s, m) + \epsilon_{sm} > \bar{V}(Z_s, m') + \epsilon_{sm'}] \qquad \text{for all } m, m' \text{ in } M. \tag{9}$$

Further assume that $\bar{V}(Z_s, m)$ can be split into two additively separable parts:

$$\bar{V}(Z_s, m) = \bar{Q}(Z_s, l) + \bar{V}_l(Z_s, m|l), \tag{10}$$

with the first term depending only on the quantity l, while the second term depends on the l vehicles in bundle m. Each component is then assumed to be a linear function of parameters and household and vehicle characteristics:

$$\bar{V}_l(Z_s, m|l) = X_{sm}\beta_l \tag{11}$$

$$\bar{Q}(Z_s, l) = Z_s\alpha_l, \tag{12}$$

where X_{sm} includes both household attributes Z_s and vehicle attributes X_m and β_l, α_l are parameter vectors. The demand function for household s can now be estimated empirically by specifying characteristics X_{sm} and Z_s and the distribution of ϵ_{sm}.

Some complication is added to the model because prices of a durable should not affect demand directly. Rather, consumers are assumed to respond to the "expected capital cost" of each vehicle. In the context of this model the relevant fixed costs of vehicle ownership are the expected depreciation, repair, and capital costs incurred during the next period. The expected capital cost for a vehicle of type n is thus:[6]

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[5] The scrap function is also forced to be continuous by assuming $R_n(P_n)$ to be linear in the neighborhood of δ_n.

[6] Conceptually, other fixed costs of ownership (e.g., insurance, registration fees) should be included. The omission of any relevant costs, due to lack of data, creates problems for estimation only to the extent that these costs vary by vehicle type in a way not captured by the included dummy variables.

$$ECC_n = P_n - (1 - \bar{R}_n(\bar{P}_n))\bar{P}_n\rho - \bar{R}_n(\bar{P}_n)\delta_n\rho + C_n(\bar{P}_n), \tag{13}$$

where

P_n = the current price of n;
$\bar{P}_n$ = the expected future price of n (next period);
$\bar{R}_n(\bar{P}_n)$ = the next period's expected scrappage probability;
δ_n = the scrap value of vehicle n;
$C_n(\bar{P}_n)$ = the expected repair cost during the period;
ρ = the consumer discount rate.

The preceding equation is dependent on estimates of future prices. For empirical work a specific expectational process will be used, but for the theoretical results we assume only that all consumers form identical expectations in some manner with the following restrictions to exclude speculation:

$$P_n > \bar{P}_n \qquad \text{for all } n;$$

$$1 \geq \frac{\partial \bar{P}_n}{\partial P_n} \geq 0;$$

$$\frac{\partial \bar{P}_n}{\partial P_j} \leq \frac{\partial \bar{P}_n}{\partial P_n}, \qquad n \neq j.$$

The vehicle demands for consumer s are given by $H(m|Z_s, M)$, the probability that household s chooses bundle m. If there are many consumers who are observationally identical to s, then $H(m|Z_s, M)$ can be considered the continuous demands of a representative consumer of type s. Furthermore, the demands of representative consumer s for vehicle type n can be expressed as

$$D_n^s(P, X, Z_s) = \sum_{m=1}^{M} H(m|Z_s, M)k_m^n, \tag{14}$$

where k_m^n is the number of type n in package m. If there are W_s consumers in group s, then the continuous demand of group s for type n is $W_sD_n^s$. Furthermore, assuming the economy contains $s = [1, 2, \ldots, S]$ distinct consumer types, then aggregate demands are the weighted sums of market segment demands

$$D_n = \sum_{s=1}^{S} D_n^s W_s = \sum_{s=1}^{S} W_s \sum_{m=1}^{M} H(m|Z_s, M)k_m^n, \tag{15}$$

where H is a function of the entire set of vehicle attributes including all current and expected future prices.

□ **Market equilibrium.** Equilibrium during each market period is defined as market clearing in each vehicle market. At the beginning of each period, consumers have endowments of vehicles from previous periods and receive an exogenous endowment of the composite commodity, Y. Each consumer then trades for his optimal consumption bundle of vehicles and Y. New car producers sell vehicles in exchange for Y and redistribute profits (if any) to consumers, while the scrap sector buys old vehicles from consumers at the scrappage price δ. Thus, the sectors interact as consumers demand both vehicles and Y, while producers demand Y and provide vehicles and scrappers demand vehicles and provide Y.

The necessary equilibrium conditions are

$$S_n(P) + Q_n = D_n(P) + R_n(P), \qquad n = 1, \ldots, N, \tag{16}$$

where

P = the price vector in terms of *numeraire;*
$S_n(P)$ = the supply of n at prices P;
Q_n = the stock of n;
$D_n(P)$ = the demand for n;
$R_n(P)$ = the scrappage "demand" for n;

and prices adjust until (16) holds.

Walras' law ensures that the market for the composite commodity, Y, will clear when all vehicle markets clear. The equilibrium price vector then has N elements, and can be shown to exist under general conditions when using standard general equilibrium methods. Uniqueness of the equilibrium can also be established provided that income effects are restricted.[7]

3. Model estimation

■ This section describes the empirical models used in the simulation system. Two models (scrappage, demand) have been econometrically estimated, while the third (manufacturer supply) has been simplified by the assumption of constant returns to scale and the resulting fixed-price supply specification. Thus, new car prices are assumed to be exogenous to the simulation system.

Three major data sources have been used in model estimation. First, vehicle-attributes data are used to identify vehicle characteristics for scrappage and demand models and to provide a description of manufacturer supply decisions. Second, information about automobile registration is used to calculate vehicle scrappage rates. Finally, a household survey is used as the primary data source for econometric demand estimation. We briefly describe each of these data sources below; more detail appears in Berkovec (1983).

The file of vehicle attributes, originally developed by Cambridge Systematics Inc. (CSI), contains information about 831 different makes and models of vehicles for model years 1967–1978. Automobile characteristics available in the file include price, weight, miles per gallon, and seating space.[8] For the demand model estimation, vehicles were grouped into 131 classes based on 13 size/type and 11 vintage classifications with characteristics of each class defined as the weighted mean of the characteristics of vehicles in the class. These groupings, described in Table 1, are somewhat subjective, but are roughly aligned with industry marketing classifications.

Automobile registration numbers are compiled annually from state registration records by the R. L. Polk Co.[9] For this analysis, national level Polk figures were obtained for 1977 and 1978 to estimate vehicle scrappage rates and calibrate the simulation model. These data are then used as true population totals by vehicle type as of June 1977 and June 1978.

The household survey data come from the National Transportation Survey, a home interview survey fielded in June 1978 by CSI and Westat Inc. for the National Science Foundation. Information about household and trend characteristics was gathered from 1095 households via a multistage stratified sample survey design. The information used from this survey includes detailed automobile holdings and standard socioeconomic data.

[7] The best way to establish uniqueness is to represent the model as a single consumer model. The essential requirement for this model is that contemporaneous income shifts caused by changing values of vehicle endowments do not affect demands for vehicles. For more detail see Berkovec (1983).

[8] Miles per gallon figures are EPA city estimates. These data are potentially flawed, but the EPA is the most comprehensive source of *MPG* data available. See CSI (1980) for more detail on data collection procedures.

[9] Data are collected from all states except Oklahoma, which will not allow access to state registration data.

TABLE 1 Vehicle Classification Scheme*

Class Number	Description	
1	Domestic Subcompact	(e.g., Ford Pinto)
2	Domestic Compact	(e.g., Dodge Dart)
3	Domestic Sports	(e.g., Chevrolet Camero)
4	Domestic Intermediate	(e.g., Chevrolet Malibu)
5	Domestic Standard	(e.g., Chevrolet Impala)
6	Domestic Luxury	(e.g., Cadillac)
7	Foreign Subcompact	(e.g., Toyota Corolla)
8	Foreign Larger	(e.g., Volvo)
9	Sports	(e.g., Porsche)
10	Foreign Luxury	(e.g., BMW)
11	Pickup Truck	
12	Van	
13	Utility Vehicle	(e.g., Jeep)

* Each class is divided into each of the 10 model years 1978–1969. Class #131 is composite "old car" for all pre-1969 models.

☐ **Scrappage model estimation.** The scrappage model is given by equation (6), which relates the scrappage probability of vehicle i in period t to vehicle characteristics and prices. Taking logarithms of (6) results in

$$\ln (R_n/Q_n) = \beta_0 + X_n\beta_1 + \beta_2 P_n + \beta_3 P_n^2 + \mu_n, \tag{17}$$

where R_n/Q_n is the scrappage probability of type n. This equation can be estimated by least squares methods using observations on realized scrappage rates instead of scrappage probabilities.[10] Realized scrappage rates in 1978, R_n^{78}, are calculated as

$$R_n^{78} = (Q_n^{78} - Q_n^{77})/Q_n^{77} \tag{18}$$

with

Q_n^{78} = the stock of n in June 1978
Q_n^{77} = the stock of n in June 1977.

Vehicles less than four years old were excluded from the sample because manufacturers were still selling old inventory. In addition, several older vehicle types were eliminated owing to increasing registrations.[11] The resulting sample consisted of 531 vehicle types.

The estimates of the scrappage model are presented in Table 2. To avoid bias due to correlation of errors μ_n and vehicle prices, these estimates use excluded vehicle characteristics as instruments for prices.[12]

The estimated price coefficients have the expected signs and are significant with the expected negative linear term and a positive quadratic. These coefficients cause scrappage rates to decrease with increasing price until about $4,500. The quadratic form (see

[10] This substitution induces a minor degree of heteroskedasticity, which is corrected for by GLS estimation. See Berkovec (1983).

[11] In particular, some used models of Mercedes and BMW show increases in registrations over the year. Either there are imports of these vehicles or, as has been suggested, there is a small industry resurrecting previously scrapped luxury cars.

[12] Previous literature on automobile scrappage (e.g., Parks, 1977) has been very concerned with potential correlation of prices and errors, as a low price could be caused by a high repair cost or scrappage probability. The linear model used here allows for an explicit test of the exogeneity of prices using a Hausman instrumental variables test. The test rejects exogeneity of prices. Somewhat surprisingly, the instrumental variables estimate indicates a stronger effect of prices on scrap rates, contrary to the expected negative correlation of prices and errors in equation (17).

TABLE 2 **Scrappage Model Results: Instrumental Variables Estimates for Price Terms**

Variable	Coefficient	*T*-Statistic
CONSTANT	−.5906	−1.212
PRICE	−2.218	−4.102
*PRICE***2	.2630	3.923
D67	−.02039	−.342
D68	−.01180	−.0282
D69	−.0784	−.1732
D70	−.0448	−.1146
D71	.0820	.2804
D72	.0539	.2610
D73	.01667	.1277
CLASS2	−.3778	−2.33
CLASS3	.0455	.265
CLASS4	−.3165	−1.824
CLASS5	−.6745	−2.646
CLASS6	−.4180	−1.696
CLASS7	−.0935	−.5190
CLASS8	.0277	.1150
CLASS9	.5480	1.390
CLASS10	−.3333	−.7670
CLASS11	.5574	1.799
CLASS12	.5146	1.574
CLASS13	1.200	2.611
WEIGHT	.0928	.6688
OLD-TRUCK	−.7750	−3.498

Number of Observations 531
Standard Error of Regression .508
Sum of Squared Residuals 131
Exogeneity Test Value = 5.99 distributed as $\chi^2(2)$ (Rejects hypothesis of exogenous prices at 5% level.)

D— = Dummy for indicated model year, e.g., *D67* is dummy for 1967 model year.
CLASS2 = Dummy variable for *CLASS2*—Domestic Compacts.
WEIGHT = Vehicle curb weight.
OLD-TRUCK = Dummy variable if truck (classes 11–13) and older than 7 years.
PRICE = Current price (June 1978) in thousands of 1978$.

footnote 4) causes scrappage to increase with price after this point, but it is more than two standard deviations above the mean price in the sample.

□ **Demand model estimation.** The demand model for an individual consumer is completed by assuming a specific distribution of the errors in equation (8). The ϵ's are assumed to follow the generalized extreme value distribution leading to nested or "tree" logit probabilities. The choice probabilities can then be written as:

$$H(m|Z_s, M) = \Delta(l|Z_s, M)\Gamma(m|l, Z_s, M) \tag{19}$$

$$\Delta(l|Z_s, M) = \frac{\exp[Z_s\alpha_l + \theta I_{ls}]}{\sum_{k=0}^{L} \exp[Z_s\alpha_k + \theta I_{ks}]} \tag{20}$$

$$\Gamma(m|l, Z_s, M) = \frac{\exp[X_{sm}\beta_l]}{\sum_{k=1}^{M_l} \exp[X_{sk}\beta_l]} \tag{21}$$

$$I_{ls} = \ln \sum_{k=1}^{N_i} \exp[X_{sk}\beta_l], \tag{22}$$

where

α, β, θ	are coefficient vectors;
l	indexes vehicle quantities;
X_{sm}	is the vector of household s and vehicles bundle m attributes;
m	indexes vehicle bundles;
Z_s	is the vector of attributes of household s;
M_l	is the subset of M containing l vehicles.

Equations (19) through (22) express the probabilistic demands of household s as the product of two multinomial logit probabilities. The second, Γ, is the conditional probability of choosing automobile bundle m, given choice of quantity l. The other, Δ, is the marginal probability of choosing level l with the inclusive value term, I, included as an independent variable.

The nested multinomial logit model is a generalization of the multinomial logit model, which allows for a partial relaxation of the property of independence of irrelevant alternatives. In the nested multinomial logit model, the independence of irrelevant alternatives holds locally within each level of the nest, but not globally across different levels, and thus allows greater flexibility in the similarity patterns of the ϵ's.[13]

The nested multinomial logit model of (19) was estimated by using a sequential maximum likelihood method. The conditional probability, Γ, is estimated first by using a simple multinomial logit algorithm with choice sets reduced by alternative sampling. The sampling procedure forms an artificial choice set for each household by taking the chosen alternative and randomly adding a fixed number of alternatives from the remainder of the choice set. This procedure can be shown to yield consistent estimates of the β parameters of equation (21) (McFadden, 1978). For this estimation, the sampling procedure allocated to each household an artificial choice set of 15 alternatives (14 random plus the household's chosen vehicle) from the available alternatives. Model estimation then proceeds as if the choice was actually made from the reduced set of 15.

The marginal probability model of automobile number, $\Delta(j|Z_s, M)$, is then estimated as a multinomial logit model with the β estimates from the first stage used to form estimates of I_{js}, the inclusive value, which is used as an independent variable. This procedure provides consistent estimates of the α parameters of the marginal model, but biased estimates of their standard errors.

Definitions of variables appear in Table 3. Estimates of the automobile demand functions are presented in Tables 4 and later also in Table 7. Four models were estimated, an ownership level model with choice of 0, 1, 2, or 3 vehicles, and three type choice models conditional on ownership of 1, 2, or 3 vehicles, respectively. To ease computational requirements for the simulations, the logit utility function for the three-car type model, $X_{sm}\beta_3$, is specified as the sum of the individual vehicle utilities.[14] This specification is restrictive in that it

[13] The similarity patterns of the unobserved variables are given by the θ parameters. If $\theta = 1$, the model reduces to a simple multinomial logit model. For a nested logit model to satisfy utility maximization, $0 < \theta \le 1$.

[14] With this restriction the conditional choice probability for the triple ijk, $P(ijk)$, can be expressed as the product of three independent terms. $P(ijk) = P(i)P(j)P(k)$, and demand function evaluation for each consumer requires only 131 probability calculations. If specialization is allowed, demand function evaluation requires a triple loop over the vehicle set or 366,145 probability calculations for each consumer. The restriction thus eases the computational requirements of the *simulation* dramatically.

TABLE 3 Variable Definitions*

Variable Name	Definition
CAPCOST	Expected capital cost if income less than \$10,000/year (in \$1,000s per year).
CAPCOST2	Expected capital cost if income between \$10,000–25,000 per year.
CAPCOST3	Expected capital cost if income > \$25,000.
CAPCOST4	Expected capital cost if income is unreported or missing.
OPCOST	Operating cost of vehicle in cents/mile (local gas price/*MPG*).
SEATSPACE	10 × number of seats in vehicle = front + rear shoulder room (inches)/2.5.
SEAT2	*SEATSPACE* if household has 5 or more members.
TRUCK	1 if vehicle is pickup truck, 0 otherwise.
VAN	1 if vehicle is van, 0 otherwise.
UTILITY	1 if vehicle is utility vehicle, 0 otherwise.
LNCL	Log of the proportion of make/models in class to total make/models.
OLD	1 if class #131, 0 otherwise.
AGE	1978—model year.
NEW	1 if model year 1977 or 1978.
NEWTRUCK	1 if truck, van, or utility and *NEW*, 0 otherwise.
FOREIGN	1 if foreign car—class types 7–10, 0 otherwise.
SPORTS	1 if sports car—class type 9.
SEATDIFF	For two-car model only, absolute difference in seat space = $\lvert \text{seatspace}^a - \text{seatspace}^b \rvert$ for pair.

* For multiple vehicle models all variables are sums over all vehicles in package.

TABLE 4 Auto Type Choice Model Coefficients

Variable Name	1-Car		2-Car		3-Car	
	Coeff.	*T*-Stat.	Coeff.	*T*-Stat.	Coeff.	*T*-Stat.
CAPCOST1	−2.240	(3.8)	−.9522	(1.9)	−2.547	(1.0)
CAPCOST2	−.826	(1.6)	−.8423	(2.3)	−1.000	(1.3)
CAPCOST3	−.653	(.41)	−.1533	(.38)	−.858	(1.2)
CAPCOST4	−.653	(1.1)	−.2731	(.73)	−.110	(.98)
OPCOST	−.199	(1.3)	−.1159	(.97)	−.1097	(.55)
SEATSPACE	.104	(2.3)	.0969	(2.6)	.052	(1.2)
SEAT2	.089	(2.2)			.0090	(.28)
TRUCK	4.988	(5.2)	3.5070	(4.7)	2.265	(1.9)
VAN	−.358	(.31)	−1.137	(1.9)	−1.137	(.91)
UTILITY	−2.000	(***)	−.1496	(.28)	−.715	(.91)
LNCL	1.531	(6.2)	1.0630	(6.2)	.927	(2.8)
OLD	−.849	(1.2)	.8713	(1.6)	1.136	(1.0)
AGE	−.166	(2.4)	−.1057	(1.9)	−.195	(1.9)
NEW	−.538	(2.1)	−.4299	(2.2)	−.688	(1.6)
NEWTRUCK	.727	(1.2)	1.3130	(4.0)	1.715	(2.4)
FOREIGN	−.571	(2.1)	−.2894	(1.3)	−.547	(1.3)
SPORTS	1.593	(1.2)	.7894	(.80)		
SEATDIFF			.0440	(2.6)		
LL(*)	−678.1		−477.5		−72.4	
LL(0)	−957.9		−945.1		−200.4	
Number of Observations	364		349		74	

LL(*) is log likelihood value at estimated coefficients.
LL(0) is log likelihood value at all coefficients set equal to 0.
*** No utility vehicles were chosen in the one-car sample so that this coefficient could not be estimated. Its value was set (somewhat arbitrarily) at −2.

eliminates functional specialization in three-vehicle households. Some specialization is allowed in the two-car model through the *SEATDIFF* variable, as the exclusion of this term was found to have a significant effect on other parameter estimates.

The calculation of user cost as defined in equation (13) requires some elaboration. A simple expectational rule was assumed for future prices:

$$\bar{P}_n = \alpha_n P_n, \tag{23}$$

where $\bar{P}_n$ is next year's expected price of type n. The α_n factors were estimated by a cross section regression

$$\ln (P'_n/P_n) = c + a_j + b_v + e_n, \tag{24}$$

where

$\alpha_n \equiv c + a_j + b_v$;
P_n = price of type n in 1978;
P'_n = price of one year older version of n in 1978;
a_j = constant for vehicle class j;
b_v = constant for model year v;
c = constant;

and where type n is of class j and model year v.

In addition, the expected scrappage rate is assumed to be the one that the scrappage model predicts at next year's expected price. Repair costs, $C_n(P_n)$, are calculated by using the scrappage model as the mean of the truncated repair cost distribution:

$$C_n(\bar{P}_n) = -\int_0^{\bar{P}_n - \delta_n} xR'_n(x)dx, \tag{25}$$

where R' is the price derivative of the scrappage probability. The user cost calculations are completed by assuming a consumer discount rate of 5% and a constant scrap value of \$100.

The coefficients of the cost terms in the model, *CAPCOST* and *OPCOST*, are all of the expected sign, but generally have low significance levels. A useful way of summarizing the capital/operating cost tradeoff is the marginal rate of substitution as shown in Table 5. These numbers exhibit wide variation across income levels with a 1¢/mile decrease in operating cost "worth" a minimum of \$43/year and a maximum of \$997/year in expected capital cost. The rational tradeoff depends on mileage driven, with a marginal rate of substitution of \$43/year being "rational" if the anticipated mileage is 4,300 miles/year.

A second marginal rate of substitution table is given for capital cost versus seating space (Table 6). Implied valuations of seating space are quite high for some households, with larger households placing a higher premium on seating space. It should be stressed that an extra "seat" is a large addition to the room in a car as new subcompacts have 3.74 seats, while new full size cars have 4.83 seats.

TABLE 5 **Marginal Rates of Substitution: Capital Cost vs. Operating Cost (\$ value of a 1¢/mi. decrease in operating costs)**

Income Level	Vehicle Quantity		
	1	2	3
1	89	122	43
2	240	138	110
3	605	757	128
4	305	424	997

TABLE 6 Marginal Rate of Substitution: Capital Cost vs. Seating Space ($ value of a 1 seat increase in seating space)

Income Level	Vehicle Quantity		
	1	2	3
1	464	102	20
2	1259	115	52
3	3161	632	60
4	1593	355	472

The *LNCL* variable is included to capture the increased attractiveness of classes that include many different makes and models. The justification for this comes from assuming a more involved logit model with a make/model choice nested under the current number/class choices. The variable *LNCL* is then an approximation to the "inclusive value" from this level of nesting.

The auto quantity model estimates are presented in Table 7. The only explanatory variables are inclusive values and alternative-specific dummies. All inclusive value coefficients are in the appropriate 0–1 range and significantly different from both 0 and 1. In estimating this model, multiple car alternatives were made unavailable if the number of cars exceeded the size of the household (e.g., a one-person household has only a choice of 0–1 cars). This restriction had little effect on inclusive value coefficient estimates.

4. Simulation system

■ The automobile market simulation system combines the empirical scrappage and demand models with exogenous data to forecast the evolution of the vehicle stock over time. Each simulation starts from a base year with known attributes and quantities for each of the 131 vehicle classes. The first simulation period then uses exogenous values of the population weights, new car attributes and prices, and policy variables as inputs to the demand and scrappage models to create forecasts of consumer demands, new sales, and scrappage for given prices. Prices are then adjusted until supply and demand are equal for every vehicle type as in equation (16). The equilibrium consumer holdings in the first period then become the vehicle stock data for the next period, and the simulation proceeds using new second-period values for the exogenous variables. This procedure is then repeated for future periods

TABLE 7 Auto Quantity Model Coefficients (auto ownership model: 4 alternatives (0, 1, 2, 3 cars))

Variable Name	Coefficient	*T*-Statistic*
Inclusive Value 1	.1088	2.26
Inclusive Value 2	.7452	5.00
Inclusive Value 3	.6475	5.74
1CAR Constant	.8878	9.25
2CAR Constant	−1.855	2.88
3CAR Constant	1.343	9.10

$LL(*) = -1111.$
$LL(0) = -1240.$
Number of observations = 1048.

* Unadjusted standard errors.

with the simulation system predicting equilibrium vehicle prices and holdings in each forecast period on the basis of the preceding period's holdings, current new car specifications, gasoline price, and household characteristics.

As described above, each forecast period requires the calculation of an equilibrium price vector. Equilibrium prices are computed iteratively by using Newton's method, where prices are adjusted on the basis of the current vector of excess demands, $E(P^t)$, and the Jacobian matrix of first derivatives of excess demands, $J(P^t)$:

$$P^{t+1} - P^t = -\lambda J(P^t)^{-1}E(P^t) \tag{26}$$

where λ is a stepsize parameter and t indexes price iterations. For small λ, Newton's method can be shown to converge to the unique equilibrium price vector if $J(P)$ is everywhere nonsingular. For the model used here, the restrictions on income effects needed to show uniqueness also ensure that $J(P)$ is nonsingular owing to the convexity of the indirect utility function. Thus, convergence to equilibrium prices is guaranteed. Newton's method requires repeated inversion of the Jacobian matrix. Since the Jacobian is a 131 by 131 matrix, this could be a computationally costly procedure. The computational needs of Newton's method are reduced in this analysis, however, by taking advantage of the special structure of the Jacobian.[15]

□ **Simulation data.** The simulation system requires estimates of household population sizes and characteristics and new vehicle characteristics for each simulation period. This section briefly describes the data sources and the methods used to set initial values for the simulation model and to construct the base-case scenario. A more detailed discussion of data sources is contained in Berkovec (1983).

To produce aggregate demand estimates, the demand models of Tables 4 and 7 require estimates of household populations in 12 categories (4 household size groups by 3 income categories). These population values were based on Bureau of the Census projections and estimates from the 1978–1982 Current Population Surveys. Census estimates for the necessary categories were found for 1978, with equivalent tables for 1979–1981 requiring adjustments only for inflation. Population weights for 1982–1990 were created by using census estimates of household totals, income levels, and mean household sizes for this period. An iterative proportional fitting technique was then used to combine the census data into a joint contingency table. The resulting population forecast shows a steady growth in total households from 77 million in 1978 to 98 million in 1990, with income levels increasing except for the 1980–1981 period. A major trend of the population forecast is a steadily declining average household size.

The vehicle attributes file, used for model estimation, served as the primary source of automobile characteristic data in the simulation. This file, containing data on 1978 and earlier model years, was updated to 1983 by using published data sources and (inflation-adjusted) list prices for the 1979–1983 period. The vehicle offerings for the 1984–1990 period are assumed to be identical to the 1983 offerings in attributes and prices.

The remaining exogenous variable is gasoline price. Actual gasoline prices as reported in *The Oil and Gas Journal* were used for 1978 to 1983. National average prices for major brand regular were used. Gasoline prices after 1983 were assumed to be constant at the 1983 level. The resulting gasoline price forecast shows gasoline prices rising from 64¢ per gallon in 1978 to 97¢/gallon in 1981, and then declining to 78¢/gallon in 1983 and thereafter.

The simulation model has been calibrated to match the 1978 base year as closely as possible. Calibration was done by estimating a constant term for each vehicle type in the

[15] Specifically, the Jacobian for this model can be written as the sum of a diagonal matrix and K rank 1 matrices. This type of matrix, labelled Identity-Outer Product in Berkovec (1983), requires only a K-dimensional inverse to calculate the full inverse. The required dimension of inverse in this analysis is 48.

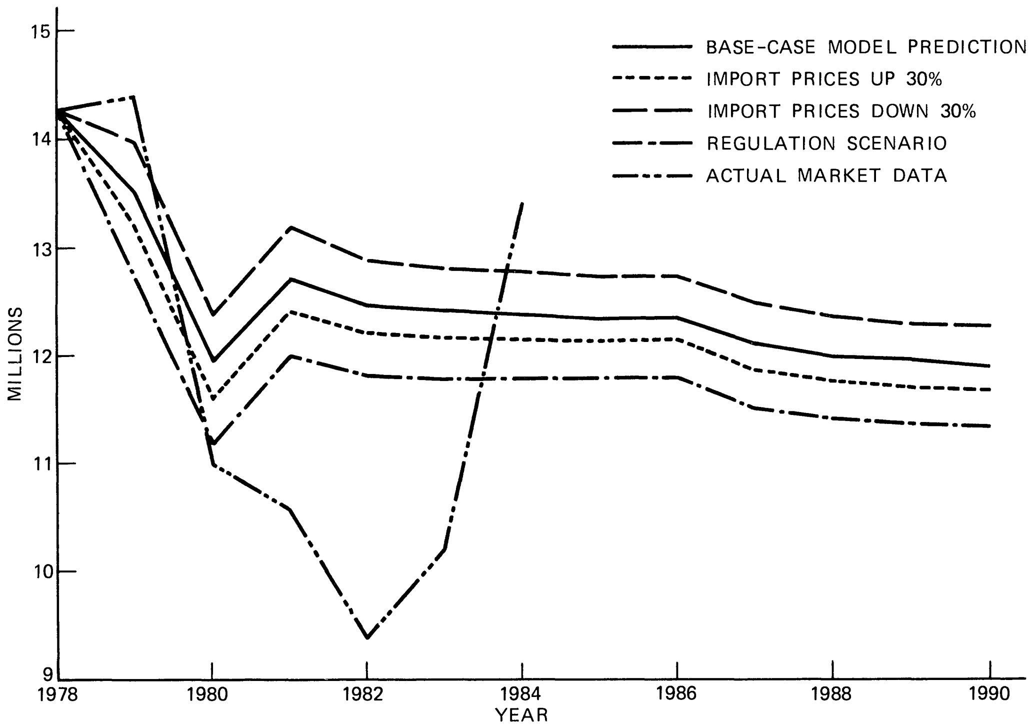
demand equation to ensure that aggregate demands predicted by the model in 1978 at observed 1978 prices exactly match the actual 1978 stock for each vehicle type. As vehicle stock data for June 1978 were used in the calibration procedure and the model predicts model year sales rather than calendar year sales, 1978 model year registrations require adjustment for the incomplete model year. The adjustment used was to assume that the entire 1978 model year production had actually been sold by June 1978.

□ **Simulation results.** The simulation system has been used to derive results for the automobile market over the period 1978–1990 for several scenarios. Some results are shown in Figures 1 to 4.[16] The discussion of model results will focus first on a description of the general trends evident in the base-case simulation. A brief discussion of the results of other scenarios will follow. Finally, we shall compare the model forecasts for the 1978–1984 period with observed market outcomes during this time period.

The base-case scenario simulation shows steady growth in the size of the automobile stock from fewer than 125 million vehicles in 1978 to nearly 160 million vehicles in 1990. This nearly 30% increase in the vehicle stock corresponds to the 27% increase in the total number of households assumed by the base case. Despite the rapid increase in the total number of vehicles, new vehicle sales (shown in Figure 1) are predicted to fall throughout the simulation period, with average new car sales during the latter part of the 1980s almost 20% below 1978 levels. These predicted sales declines are more dramatic for domestically produced vehicles than for imports as the predicted import market share rises in the 1978–1981 period and then, by assumption, remains stable (Figure 2).

FIGURE 1

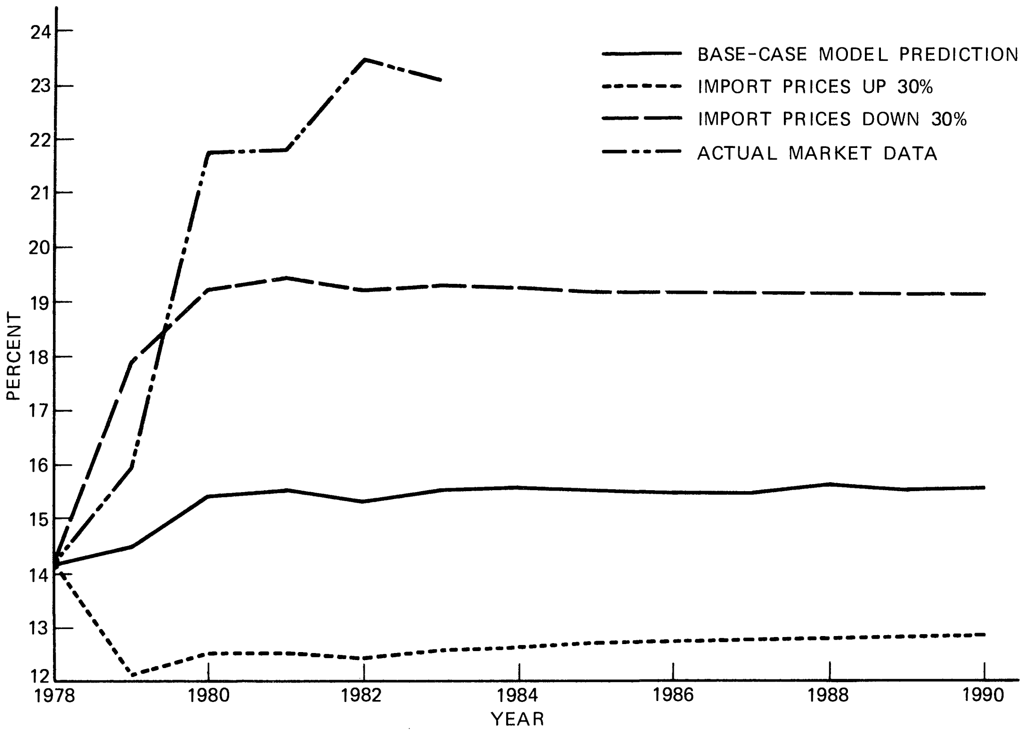
NEW VEHICLE SALES



[16] The results shown are aggregate model predictions. Forecasts are possible at much more disaggregate levels (e.g., 1983 holdings of 1979 subcompacts by three-person households with income above $25,000).

FIGURE 2

IMPORT SALES SHARES



The predicted growth in the vehicle stock occurs largely because of the prediction of declining scrappage rates. As shown in Figure 3, scrappage levels are predicted to be below 1978 levels in nearly all forecast periods despite the substantially larger fleet of used vehicles. The scrappage predictions fluctuate during the simulation period with the highest scrap quantities observed during the 1979–1981 period of rising gasoline prices. Gasoline price increases cause increased scrappage by reducing the aggregate demand for vehicles. This leads to lower average prices for used vehicles (especially fuel inefficient ones) and correspondingly higher scrappage probabilities.

The base-case simulation predicts a rapid increase in average new car fuel efficiency during 1978–1982. This increased efficiency is caused both by higher gasoline prices and by the rapid improvement in the fuel efficiency of the available new cars from 1978–1982 (caused partly by higher government fuel efficiency standards). A constant average new car miles per gallon after 1983 is predicted as a consequence of the assumed constant real gasoline prices and the unchanging characteristics of new vehicles.

The increased new car fuel efficiency along with the gradual retirements of older vehicles cause the predicted average *MPG* of the vehicle fleet to increase steadily over the 1978–1990 period as shown in Figure 4. Fleet fuel efficiency improvements are most rapid in the early part of the period as the inefficient early 1970s vintage vehicles are scrapped because of age and increased gasoline prices. Fleet efficiency continues to increase significantly even after fuel price increases stop as more efficient new cars continue to replace less efficient older models. Overall, the average fleet *MPG* increases by nearly ⅓ from 15 in 1978 to nearly 20 in 1990.

Three alternative scenarios are also shown in Figures 1 to 4. The additional scenarios are all pricing changes for new cars after the 1978 model year. The first policy, labelled Regulation, simulates the effect of increased pollution requirements imposed by government.

FIGURE 3

SCRAPPAGE LEVELS

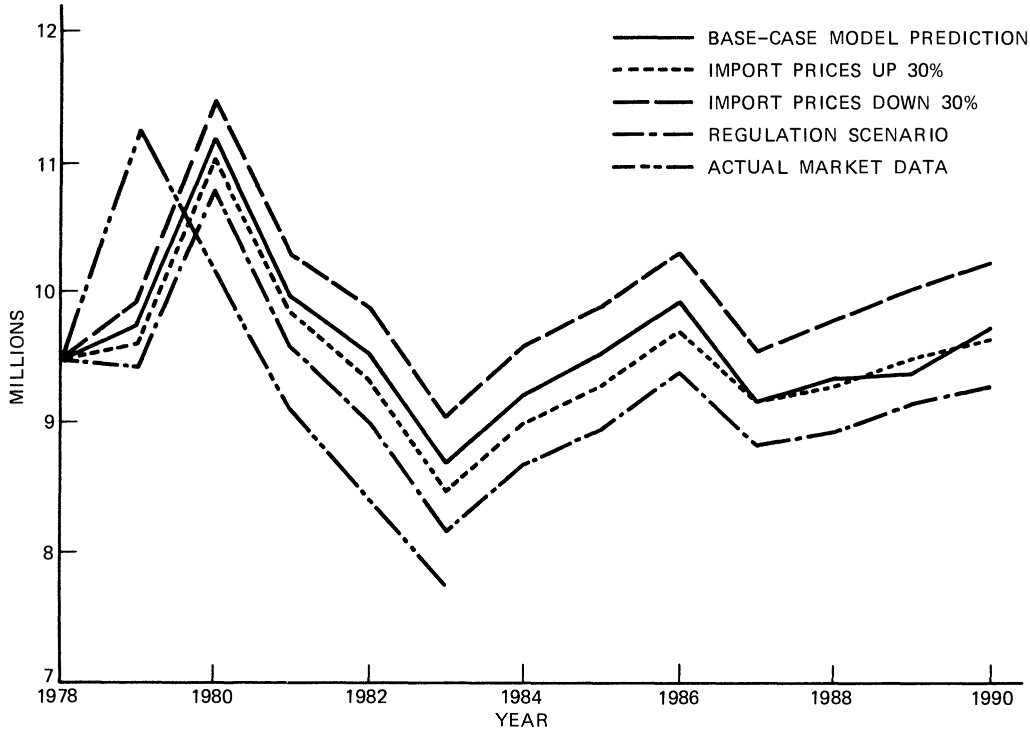
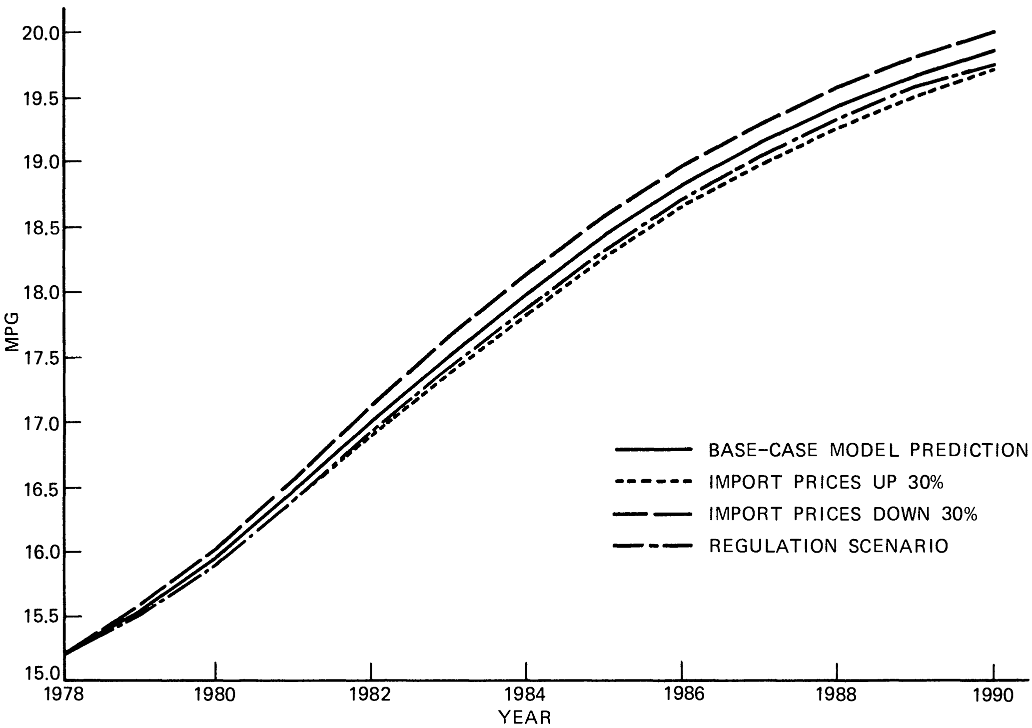


FIGURE 4

FLEET AVERAGE FUEL ECONOMY



The regulation policy assumes that increased regulation adds \$500 to the price of each new vehicle but confers no benefits on the owners of new vehicles. The other two scenarios, Import Price Up and Import Price Down, simulate the effects of changing exchange rates or imposition of tariffs. These scenarios change all import prices for 1979–1990 by 30% from the prices assumed in the base case. Prices of new domestic cars are assumed (unrealistically) to be unaffected by the change in import prices.

The policy simulations exhibit the same basic trends as the base case. Price increases for new cars reduce sales of new cars and increase used car prices and so cause lower scrappage levels. The price increases lower the overall quantity of vehicles and increase the average age of the vehicle stock. New car price reductions have the opposite effects. Price increases (decreases) only for imports have the additional effect of increasing (decreasing) sales of domestic cars. Predicted own price elasticities are somewhat less than unity as a \$500 new car price increase (~7% increase) reduces total 1979–1980 sales by about 5%. Import price increases (decreases) of 30% result in a −20% (+28%) change in total import sales. The cross effects of import prices on domestic sales are predicted to be relatively small with the 30% import price increase reducing import sales by 4.5 million cars but increasing domestic sales by only 2.5 million from 1978–1990.

The three different new car price scenarios have small but noticeable effects on the average fuel economy of the fleet as shown in Figure 4. The decrease in fleet average *MPG* caused by new vehicle price increases has two potential causes. First, price increases reduce new car sales and retard scrappage, and thus cause the vehicle stock to be older and less efficient on average. Second, the price changes can alter the mix of new vehicles. The regulation scenario causes fuel economy to fall on average by shifting the distribution of the stock toward older vehicles. The uniform price increase of the regulation scenario has virtually no effect on the new sales mix,[17] but a substantial effect on scrappage levels (Figure 3). The import price scenarios have effects on both the mix of new cars and on the age distribution of the fleet.

These results are illustrative of the policy sensitivity of the simulation model. Other policies considered in Berkovec (1983) include gasoline price changes and differentiated "gas guzzler" new car taxes. These simulations indicate that average fuel efficiency increases with increasing gasoline price both because of more efficient new cars and because of more rapid scrappage of used cars. Gas guzzler taxes are predicted to have virtually no effect on aggregate fuel economy, as increased new car fuel efficiency is completely offset by the longer lives of less efficient older cars. In some cases, gas guzzler taxes on new cars actually reduce average fuel economy as the scrappage effect is larger than the direct substitution effect.

It is of interest to compare the forecasts of the simulation model with the observed market outcomes for the period since 1978. Despite some differences in definitions and analysis methods between model quantities and available data, this comparison provides a useful guide for examining the performance of the model and for identifying potential areas for improvement. A strong caveat should be added that the model cannot be expected to predict year-by-year market changes accurately, as the world is more complex than can be represented by such a simple model; rather one should expect a good model to identify general trends in the market.

The base-case model predicts nearly the same growth rate of the vehicle stock as shown in registration data for 1978–1982. Sales levels, as shown in Figure 1, are underpredicted in 1979 and overpredicted for 1980–1983. The model does show a substantial drop in sales in 1980 due to the large (~30%) gasoline price increase in that year, but does not predict the subsequent sales decline of the early 1980s. Macroeconomic shocks were important

[17] This is a direct consequence of the demand model specification. The only changes are results of a different consumer mix purchasing new cars.

during this period, and these are not well represented in the base-case scenario.[18] The model sales predictions can be interpreted as average sales abstracting from macroeconomic effects; on this basis, sales projections appear to be reasonable with positive errors in recessionary years balanced with compensating negative errors in other years.

A more substantial discrepancy in the model predictions is shown in Figure 2, as import market shares are dramatically underpredicted. As shown, import shares have risen dramatically since 1978. The model suggests that some of this change can be explained by gasoline price and measured vehicle attribute changes, but that there are other reasons for this shift (e.g., changed quality perceptions or expectations of continued rapid gasoline price increases), which have not been fully captured by the model.[19]

Overall, the simulation model forecasts appear to do reasonably well for the 1978–1982 period. Although there are discrepancies in specific areas (as would be expected because of underlying macroeconomic fluctuations), the general trends evident in the data would seem to be captured in the forecasts.

5. Conclusion

■ This article has presented theoretical and empirical models of automobile demand, scrappage, and supply. These separate components are combined into a general equilibrium model for simulating future trends in the automobile market. The simulation model allows product differentiation and consumer heterogeneity and explicitly accounts for the existence of a fixed stock of vehicles at the beginning of the forecast period. The model can provide forecasts of automobile sales, holdings, and scrappage at virtually any degree of product disaggregation.

The simulation model has been used to provide estimates of automobile market behavior for the 1978–1990 period for several policy scenarios. The simulation results indicate that automobile sales are likely to be low (relative to the 1970s) for the remainder of the decade. Although new car sales are likely to recover from the depressed levels of the early 1980s, as the average sales forecasts for 1983–1990 are well above actual 1980–1982 sales, they are unlikely to reach the levels of the 1970s. This leads to the conclusion that the output of domestic manufacturers (and automobile industry employment) is liable to remain low throughout the 1980s. This conclusion is reinforced when one considers that actual import market shares have well risen above the model forecast of 15%, and are likely to remain high for the forseeable future.

Despite the predicted decline in new car sales, the total vehicle fleet is predicted to grow rapidly throughout the 1980s as the household population continues to grow. This growth is predicted to be achieved primarily by decreases in vehicle scrappage rates which lead to longer average vehicle lifetimes. The predicted rapid growth in the number of older vehicles has potentially serious implications for automobile safety and the environment.

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[18] The model does use actual census income data for 1980–1981 in the base case, but the income sensitivity of the demand model is slight, and the income data do not show large deviations from trend at the desired level of aggregation. A more promising method of simulating recessions with this model would be to alter consumer discount rates; this has not been done.

[19] Actual list prices were used for 1979–1983. Since all available evidence suggests that, relative to domestics, list prices for imports are lower than actual transaction prices especially in the quota era, pricing and exchange rate issues do not appear to be the answer.

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