ECONOMETRIC MODELS OF THE DEMAND FOR MOTOR FUEL

PREPARED UNDER GRANTS FROM THE NATIONAL SCIENCE FOUNDATION WITH SUPPORT FROM THE FEDERAL ENERGY ADMINISTRATION

BURKE K. BURRIGRT
JOHN H. ENNS

R-1561-NSF/FEA
APRIL 1975
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Rand
SANTA MONICA, CA. 90406
PREFACE

This report was produced under Rand's continuing research program on The Evaluation of Measures to Conserve Energy, funded by a grant from the National Science Foundation, with Deane N. Morris as principal investigator. The central concerns of the program are the rapid increase in demand for energy in all sectors of the U.S. economy, the conflict between that demand and the national goal of reducing dependence on foreign energy supplies, and the implications of the conflict for governmental policymaking. The research presented here was also aided by funds from the Office of Transportation Programs of the Federal Energy Administration.

This study is one of three that describe measures and public policies for conserving energy used by automobiles. It presents econometric measures of the demand for highway motor fuel and gasoline, with particular attention to the response of gasoline use to changes in its price. The study considers both long-run and short-run (the period during which the size and characteristics of the automobile stock remain relatively constant) responses. Related research results are summarized and compared with this study's results. The report is intended primarily for economists and other analysts interested in the application of econometrics to energy policy problems.

A second report in the series develops analytic tools with which to evaluate the effects of national energy conservation measures on private transportation: R-1560-NSF, October 1974, How to Save Gasoline: Public Policy Alternatives for the Automobile, by Sorrel Wildhorn, Burke K. Burrigh, John H. Enns, and Thomas F. Kirkwood. The present report includes portions of the work that appeared in R-1560-NSF.

The third report describes the development, validation, and application of one of the models used in this study to compare energy conservation policies: R-1562-NSF, January 1975, A Generalized Model for Comparing Automobile Design Approaches to Improved Fuel Economy, by
Thomas F. Kirkwood and Allen D. Lee. It is a generalized model used for producing alternative designs of automobiles.
SUMMARY

Stimulated by the intensified national interest in gasoline conservation, several econometric studies of the response of motor fuel demand to changes in its price have recently appeared. These have some features in common, but they differ importantly in both modeling approach and empirical results. For example, almost all of the research to date suggests that the short-run price elasticity of fuel use is low—probably between -0.1 and -0.3—while estimates of the long-run price elasticity are much higher—generally between -0.65 and -0.85. But there is little agreement on the magnitude of the adjustment processes that occur in response to fuel price changes. Knowledge about those adjustments—reduction in miles driven, changes in driving behavior (e.g., driving slower), or shifts in the number and characteristics of automobiles—is important for understanding the effects of fuel conservation policy.

This report has two purposes. First, we review and evaluate recent econometric research; second, we compare our own methodology and results with those of related studies. We then summarize what is now known and what is still to be learned about the demand for highway motor fuel.

Our research has two components: a short-run and a long-run analysis. In the short-run analysis, we use a simple model of household decisionmaking to explain the demand for vehicle miles traveled. Our model is based on the economic theory of production; we assume that households combine three inputs—vehicle service, motor fuel, and travel time—to "produce" automobile miles driven. In the short run, families can decrease fuel consumption in two ways: by driving fewer miles and by changing their driving habits. The first represents a scale effect and the latter may be interpreted as a substitution effect; for example, by driving slower, families substitute time for fuel in the production of vehicle miles. Using this model, we derive
a short-run demand function for motor fuel using the assumption of utility maximization. The arguments of the demand function are real fuel price, the wage rate, average fuel efficiency (or miles per gallon), and automobile ownership.

In the long-run analysis, we focus on changes in automobile ownership that would result from changes in fuel prices and new and used car prices, and real personal income. A limitation of our long-run model is that it cannot directly forecast changes in the fuel efficiency of an average new car; such changes will definitely occur in response to fuel price changes as both consumers and producers alter their choices between vehicle weight classes.

We use two data bases to estimate the coefficients of the short-run demand equation. The first is a pooled time-series of state data for 1955 to 1970. Fuel consumption data by states is available only for all highway uses of motor fuel—automobiles, trucks, buses, and motorcycles. The second data base comprises national time-series data for 1950 to 1972. In this second version of the short-run demand model, only automobile fuel consumption is considered. For the long-run analysis, we use only national time-series data.

Our findings (and those of other recent studies) lead us to the following conclusions which we believe summarize the current understanding of the demand for highway motor fuel:

- The short-run elasticity of highway motor fuel use (by all vehicles) with respect to real price is low; most estimates are between -0.1 to -0.3. This result seems to hold regardless of the model specification or data base used.
- The long-run elasticity of highway motor fuel use (or of automobile gasoline use in particular) is much higher; our results and those of other investigators suggest that it is probably between -0.60 and -0.85.
- In the first year after a fuel price change, about 80 percent of the price-induced change in fuel use would be due to a change in vehicle miles traveled. The remainder would be due
to changes in driving habits that reduce fuel use per mile.

- Higher gasoline prices would initially reduce new car sales but the reduction would be transitory. However, the size of the sales decline is uncertain; our estimates of the elasticity of new car sales with respect to fuel price are between -0.7 and -1.0, while other studies suggest a lower response of -0.2 and -0.3.

- A 10 percent increase in real gasoline price would result in a 2 to 3 percent reduction in automobile ownership in the long run. However, such a decline could be offset by improved new-car fuel efficiency, which might stimulate sales.

- A given percentage increase in average vehicle fuel efficiency would not result in the same percentage decrease in highway motor fuel use. An increase in efficiency decreases the fuel cost of driving per mile; consequently, households would be likely to drive more. We estimate that a 10 percent increase in average miles per gallon would result in a 7 to 8 percent decline in fuel use.
ACKNOWLEDGMENTS

Many people from various organizations provided valuable assistance to this study. Among Rand colleagues and consultants, Kent Anderson, Marc Nerlove, and Finis Welch made helpful suggestions about our general approach. We benefited from discussions with Charlotte Chamberlain of the Transportation Systems Center, R. G. McGillivray of The Urban Institute, James Sweeney of the Federal Energy Administration, and Philip Verleger of Data Resources, Inc. All four provided us with prepublication drafts of their research. Frank Wykoff of Pomona College supplied us with a data series on permanent income.

Several Rand colleagues gave us useful comments on an earlier draft of this study. They include G. H. Fisher, F. S. Hoffman, D. N. Morris, G. R. Nelson, R. T. Smith, S. Wildhorn, R. Shishko, and J. P. Stucker. Loanne Batchelder provided much help as research assistant and programmer and Cielita Guarnes prepared the manuscript for publication.
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SYMBOLES*

\[ P_f = \text{average real price of regular gasoline} \]
\[ P_n = \text{average real price of new cars} \]
\[ P_u = \text{average real price of used cars} \]
\[ M = \text{average vehicle (auto) fuel efficiency (miles per gallon)} \]
\[ MN = \text{average new car fuel efficiency (miles per gallon)} \]
\[ F = \text{motor fuel consumption (millions of gallons)} \]
\[ A = \text{registered vehicles (millions)} \]
\[ Y = \text{disposable personal income or permanent disposable personal income} \]
\[ N = \text{U.S. new car unit sales (millions)} \]
\[ U = \text{U.S. used car stock (millions)} \]
\[ V = \text{vehicle miles traveled (millions)} \]
\[ PT = \text{truck fleet as a percent of total vehicle fleet} \]
\[ POP = \text{population (thousands)} \]
\[ DPOP = \text{driving age population (thousands)} \]
\[ UPOP = \text{percent of population residing in urbanized areas} \]
\[ H = \text{households (thousands)} \]
\[ Z = \text{unemployment rate (percent)} \]
\[ D = \text{dummy variable for safety and emission standard years} \]
\[ (= 0: \text{1952-1967}; = 1: \text{1968-1972}) \]
\[ ST = \text{dummy auto strike variable} (= -1, \text{strike year}; = +1, \text{year following strike}; = 0, \text{otherwise}) \]

*For some versions of the demand model, two sets of data are used: national time-series and pooled state time-series. Where applicable, the same symbols are used for both the state and national data.
I. INTRODUCTION

Econometric research on the demand for motor fuel has increased rapidly over the last two years as interest in national energy conservation has grown. Several recent studies seek to explain the response of motor fuel use—by all vehicles or by automobiles alone—to changes in fuel price and other economic variables. Most of these studies find that the short-run price elasticity of fuel demand is low; virtually all estimates based on recent U.S. data are in the range of -0.1 to -0.3. The studies also report long-run price elasticities between -0.65 and -0.85. In spite of the similarity in their findings, however, the studies differ sharply in their modeling approaches. Their differences are important because they affect the usefulness of the models for designing fuel conservation policy. Some models of fuel demand, such as flow adjustment models, do not distinguish among the ways in which households can adjust to permanent changes in fuel prices. In response to price increases, households may (1) reduce miles driven per vehicle, (2) use more fuel-efficient driving behavior, or (3) change the number and characteristics of the vehicles they operate. It is important to be able to measure and compare the effects of those choices, both in the short and long run, if policymakers are to anticipate the results of their actions. For example, suppose that households' primary response to increased fuel prices (due perhaps to higher gasoline taxes) is to drive less rather than shift to cars that get better mileage or reduce automobile ownership; that response would have less effect on new car sales than it would on such sectors as automobile repair and maintenance or automobile part suppliers, whose business volume is closely related to the volume of highway travel.

The present study has several purposes. First, we review and evaluate several recent econometric studies of gasoline demand. (Our list of studies is probably incomplete because much of the research
is as yet unpublished.) Second, we present an economic model of household decisionmaking with which to analyze the adjustment processes mentioned above. The basic short-run gasoline demand function that emerges from this analysis is estimated separately with pooled time-series data from states (1955-1970) and national time-series data (1950-1972). These results are presented in Sec. II. In the long-run analysis we examine the response of fuel use to price changes when the stock of automobiles is allowed to vary; the model developed has separate equations for fuel use, new car sales, and used car prices. We estimate these equations using national time-series data for 1954-1972, and present the results in Sec. III.¹

Section IV summarizes our conclusions regarding the total fuel price elasticity and its components, based on both previous research and the present study. Given the diversity of models, data sources, and estimation techniques, it is not surprising that much uncertainty remains about the various long-run processes of adjustment of motor fuel demand to fuel price. In particular, no research to date (including the present study) has successfully modeled both the changes in new car fuel efficiency (miles per gallon) and the long-run size of the automobile fleet that higher fuel prices will induce.

¹Some of the results in Secs. II and III have appeared in an earlier Rand report, R-1560-NSF, How to Save Gasoline: Public Policy Alternatives for the Automobile, by Sorrel Wildhorn, Burke K. Burright, John H. Enns, and Thomas F. Kirkwood, October 1974. Readers interested in application of the models described in the present study for projections of fuel use under varying assumptions about future gasoline prices should consult R-1560-NSF, especially pp. 56-95 and App. E.
II. SHORT-RUN FUEL DEMAND WITH FIXED AUTOMOBILE STOCK

This section focuses on short-run changes in motor fuel use. The short run is defined as the period in which the size and fuel-efficiency characteristics of the automobile stock do not change. First, we review previous research. Next, we present an economic model of vehicle mile production by households. We then use the model for empirical estimation of a gasoline demand function using two data bases: pooled time-series data from states, and national time-series data.

RELATED RESEARCH ON GASOLINE DEMAND MODELS

Previous investigators have used two general approaches: single-equation flow adjustment models, and multiequation models that explicitly include adjustments in new car sales and total automobile ownership. Below we review previous flow-adjustment models as well as equations from the automobile ownership models that use either gasoline consumption or vehicle miles as their dependent variable. Table 1 summarizes these models and elasticity estimates.

Flow Adjustment Models

Several recent attempts to estimate a demand function for gasoline have employed models of the following form:

\[ q_t = a + bp_t + cy_t + dq_{t-1} \]  \hspace{1cm} (2.1)

where \( q_t \) = gasoline consumption per capita in period \( t \),
\( p_t \) = relative price per gallon of gasoline in period \( t \),
\( y_t \) = real personal income per capita in period \( t \),
\( q_{t-1} \) = gasoline consumption per capita in period \( t-1 \)

and \( a, b, c, d \) are parameters to be estimated.

In its simplest form, the flow adjustment model states that gasoline demand this period is determined by gasoline price, real personal income, and gasoline consumption in the previous period.
The term "flow adjustment model" has been applied to this type of model because "the dynamics of consumption are viewed as an attempt on the part of consumers to bring their actual consumption closer to some desired level."\(^1\) The rationale for this specification is based on the following characterization of the adjustments to a change in one of the independent variables, such as price. Immediately following a price increase, consumers can make only small adjustments, such as forming carpools or forgoing marginal trips. Over longer periods, more adjustments can occur; for example, families can purchase more efficient autos and move closer to their work locations. An important advantage of flow adjustment models is that they capture the time-phased nature of the total adjustment to a change. The speed of adjustment is determined by the value of the coefficient of the lagged consumption term; the smaller the estimated coefficient of this variable, the faster is the adjustment to a new equilibrium position.

\(^1\) Hendrik S. Houthakker and L. D. Taylor, *Consumer Demand in the United States: Analyses and Projections*, Harvard University Press, Cambridge, Mass., 1970, p. 26. Equation (2.1) above actually is consistent with two different models of fuel demand. The first model is analogous to the dynamic stock adjustment models for natural gas developed by P. Balestra and M. Nerlove, "Pooling Cross Section and Time Series Data in the Estimation of a Dynamic Model: The Demand for Natural Gas," *Econometrica*, Vol. 34, July 1966, pp. 585-612. A major feature of this model is that total demand is divided into two components: demand stemming from use of the existing stock of vehicles and demand associated with replacements (or new cars added to the vehicle stock). Assuming constant use of the existing stock, the demand equation that emerges from this model views only fuel consumption that stems from new car purchases as being price- and income-sensitive during a given time period. The second model does not distinguish between fuel demand by the existing stocks and by new additions. Rather, it views changes in the total demand for gasoline as adjustments between actual and desired demand over time. Since both models yield identical estimating equations, the interpretation of the results is open to choice. For a more detailed discussion of these two models, including the derivation of demand equations, see Data Resources Inc., *A Study of the Quarterly Demand for Gasoline and Impacts of Alternative Gasoline Taxes*, unpublished study prepared for the Council on Environmental Quality, December 5, 1973, Apps. I, II.
This basic flow adjustment model has been estimated using different definitions of gasoline use, data periods, and estimation techniques. (See Table 1.) Two studies have estimated the pure flow adjustment model with U.S. data. Phlips obtained a one-year price elasticity of \(-0.11\); a figure of \(-0.20\) was obtained by Data Resources, Inc. using pooled time-series data from states. Using international data, Chamberlain and Houthakker and Kennedy obtained short-run elasticity estimates of \(-0.12\) and \(-0.47\).

Flow adjustment models also provide direct estimates of long-run fuel price elasticity. This is because the coefficient of the lagged consumption term measures the proportion of last period's fuel use, which is carried forward each period following a price change. Estimates of this coefficient, which are statistically significant, have varied considerably: 0.90 (Chamberlain, international model), 0.84 (Phlips), 0.70 (McGillivray), 0.70 (Data Resources, Inc.), and 0.44 (Houthakker and Kennedy). The long-run fuel price elasticities implied by these values range from \(-0.65\) to \(-1.21\) (see Table 1). Since the magnitude of long-run response remains in doubt—based on results of the flow adjustment model—other approaches that model the explicit long-run adjustment process seem to be a necessary research step if policy analysis capability is to be improved.

Two other studies have used modified flow adjustment models. In addition to the international model, Chamberlain has also used U.S. data to estimate a flow adjustment model that includes new car price as an explanatory variable. The model assumes that changes in fuel demand result from new car additions to the existing fleet. The empirical results, however, do not provide estimates of high statistical significance for the price coefficients (gasoline and new car) or the lagged consumption term. McGillivray has also adop-


\(^3\)Op. cit.


Table 1

SUMMARY OF RECENT GASOLINE DEMAND MODELS

<table>
<thead>
<tr>
<th>Author</th>
<th>Description of Model</th>
<th>Dependent Variable(s)</th>
<th>Independent Variables</th>
<th>Type of Data</th>
<th>Estimation Technique</th>
<th>Price Elasticity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Philips</td>
<td>Dynamic linear expenditures</td>
<td>Gasoline and oil consumption per capita</td>
<td>Relative gasoline/oil price, real personal income, lagged consumption</td>
<td>Annual U.S. data, 1929-1967</td>
<td>Maximum likelihood with autoregressive errors adjustment</td>
<td>-0.11^2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(1942-45 excl.)</td>
<td></td>
<td>-0.68</td>
</tr>
<tr>
<td>Chamberlain</td>
<td>Flow adjustment</td>
<td>Gasoline consumption per capita</td>
<td>Relative gasoline price, real personal income per capita, lagged consumption</td>
<td>Annual data: France, W. Germany, Netherlands, and U.K.</td>
<td>Ordinary least squares</td>
<td>-0.12^2</td>
</tr>
<tr>
<td>Houthakker and Kennedy</td>
<td>Flow adjustment</td>
<td>Gasoline consumption per capita</td>
<td>Relative gasoline price, real personal income per capita, lagged consumption</td>
<td>Annual OECD data, 1962-1972: Portugal, Italy, Austria, Belgium, Denmark, France, W. Germany, Netherlands, Norway, Sweden, U.K., and U.S.</td>
<td>Error components with autoregressive errors adjustment</td>
<td>-0.47^2</td>
</tr>
<tr>
<td></td>
<td>Flow adjustment with new car gasoline demand influenced only by price</td>
<td>Passenger car gasoline consumption per capita</td>
<td>Relative gasoline price, real personal disposable income, relative new car price, average miles per gallon of passenger cars, lagged consumption</td>
<td>Annual U.S. data, 1951-1970</td>
<td>Ordinary least squares</td>
<td>-0.06</td>
</tr>
<tr>
<td></td>
<td>Flow adjustment with new car gasoline demand influenced only by price</td>
<td>Passenger car gasoline consumption per capita</td>
<td>Relative gasoline price, per capita new car sales, gasoline consumption per vehicle, lagged consumption</td>
<td>Annual U.S. data, 1951-1969</td>
<td>Ordinary least squares</td>
<td>-0.23^2</td>
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<td></td>
<td></td>
<td>-0.76</td>
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<tr>
<td>Author</td>
<td>Description of Model</td>
<td>Dependent Variable(s)</td>
<td>Independent Variables</td>
<td>Type of Data</td>
<td>Estimation Technique</td>
<td>Price Elasticity</td>
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</tr>
<tr>
<td>Ramsey, Rasche, Allen</td>
<td>Supply/demand model with private and commercial demand equations</td>
<td>Private gasoline consumption per household</td>
<td>Relative prices of gasoline and commuter train travel, real disposable income, proportion of population aged 16-24</td>
<td>Annual U.S. data, 1947-1969</td>
<td>Two-stage least squares</td>
<td>-0.77²</td>
</tr>
<tr>
<td>Chase Econometric Associates</td>
<td>VMT/new car sales adjustment model</td>
<td>Commercial gasoline consumption</td>
<td>Relative prices of gasoline and diesel fuel, relative price of rail freight, index of ton-mile freight demand</td>
<td>-0.4²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>James Sweeney, Office of Energy Systems (FRA)</td>
<td>VMT/auto efficiency/new car sales adjustment model</td>
<td>Vehicle miles traveled in autos</td>
<td>Relative price of gasoline and oil, auto ownership, real personal income, lagged average new car price</td>
<td>U.S. annual data, 1956-1972</td>
<td>Ordinary least squares</td>
<td>-0.5²</td>
</tr>
<tr>
<td>Schuessler, Smith</td>
<td>VMT model</td>
<td>Auto vehicle miles traveled per capita</td>
<td>Auto cost of operation per mile, per capita real disposable income, unemployment rate, lagged VMT</td>
<td>U.S. annual data, 1950-1972</td>
<td>Nonlinear least squares with first-order autoregressive transformation</td>
<td>-0.12² to -0.72</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vehicle miles traveled in autos</td>
<td>CPI gas, auto stock, per capita real disposable income</td>
<td>U.S. annual data, 1955-1974</td>
<td>Ordinary least squares to</td>
<td>-0.15² to -0.25²</td>
</tr>
</tbody>
</table>

**NOTES:**
1. The Data Resources, Inc. model was estimated using four versions of the dependent variable (in per capita terms): (a) total gasoline consumption, (b) total gasoline less aviation and federal government consumption, (c) total motor fuel consumption on the highway, and (d) total motor fuel less special (diesel, etc.) consumption on highways. The model was estimated in both a linear and logarithmic form; the linear results using total gasoline consumption data are used to calculate the elasticity estimates presented above.
2. The short-run elasticity is the net elasticity of commercial demand for an equal percentage change in gasoline and diesel fuel price.
3. Estimated price coefficient used to calculate own price elasticity is at least significant at the .01 level.
ted the new car demand approach toward modelling U.S. gasoline demand. His model, which also includes a variable measuring historical gasoline consumption per vehicle, yields a short-run elasticity estimate of -0.23.

**Critique of Flow Adjustment Models**

Flow adjustment models avoid a difficult problem in econometric demand analysis: separating the stock and flow effects on the demand for gasoline resulting from a price change. The approach has two serious limitations, however. One is that these models can be used to study only one type of policy—that which involves a gasoline price change. They cannot adequately analyze other fuel conservation measures designed to increase average fuel efficiency (miles per gallon) of the vehicle stock or to change driving habits (car-pooling or limiting speed). A second and related limitation is that these models say nothing about how adjustments to fuel price changes occur, nor about the relative strengths of adjustment processes. Highway motor fuel use can be reduced by (1) driving fewer miles per vehicle, (2) operating the existing automobile stock more efficiently, (3) operating more efficient vehicles, and (4) operating fewer vehicles. The strength of each adjustment process is important for assessing the effects of policy. For example, reductions in vehicle miles may primarily affect businesses that depend on discretionary long-distance trips (e.g., vacations), whereas changes in driving habits (e.g., driving slower) may primarily affect travel time regardless of trip purpose (and thus have less effect on businesses that depend on discretionary travel). Regional fuel conservation policy may also be enhanced by a more precise understanding of these adjustment processes. Whereas driving at lower speeds may represent a change in behavior that is not region-specific, other responses such as increased car-pooling or use of public transportation are likely to be quite sensitive to locale. Past studies as well as the present study, however, do not attempt to measure such regional differences in driving habit response to fuel price changes.
Other Models of Gasoline Use

A study by Ramsey, Rasche, and Allen\(^6\) divides the demand for gasoline into two components: private and commercial. The supply side of the market is also specified explicitly; the ratio of motor gasoline supplied to the total amount of crude oil is taken to be a function of the relative wholesale prices of all distillates. The two demand equations are then estimated as part of a simultaneous equations system using the technique of two-stage least squares. Their estimates of the fuel price elasticities (see Table 1) are somewhat greater than previous short-run estimates, but generally agree with the long-run results of other research. Their results also suggest that commercial fuel demand is less responsive to price changes than is private demand.

Two other research efforts have avoided the flow adjustment approach and have instead attempted to model explicitly the changes in auto fleet characteristics and size. We discuss the aspect of these efforts that involve direct adjustments in fuel use or vehicle miles traveled. The discussion of automobile stock adjustment is presented in the following section.

Chase Econometric Associates developed a seven-equation model in which new car sales are forecast for five size classes.\(^7\) The model includes an equation for vehicle miles traveled (VMT) by private automobile in which VMT is a function of the relative price of gasoline, real personal income, and automobile ownership. The gasoline price elasticity of VMT is calculated to be \(-0.5\), considerably higher than other estimates of the short-run (one-year) elasticity of fuel demand.

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Researchers at the Transportation Systems Center have also estimated a demand equation for total vehicle miles traveled as a function of relative gasoline price, real per capita personal disposable income, and automobile stock. Their estimates of the short-run price elasticity range from -0.15 to -0.25.

James Sweeney has developed a four-equation model that includes automobile stock and efficiency adjustments; it also has an automobile VMT equation.\(^8\) (The automobile stock adjustment portion of the model is described in Sec. III.) In this equation, per capita automobile VMT is a function of per capita disposable income, the unemployment rate, per capita VMT last year, and the cost per mile of auto travel--including time cost as well as gasoline cost. Average new car fuel efficiency is forecast as a function of the real gasoline price with a second equation. It is averaged with the fuel efficiency of used cars to calculate an average fuel efficiency for the entire automobile stock. This estimate, along with the forecast of automobile VMT, is used to compute automobile gasoline use. The implied first-year price elasticity of automobile gasoline use is -0.12, while the long-run elasticity is -0.72.

**SUMMARY OF PREVIOUS PRICE ELASTICITY ESTIMATES**

Although prior studies have used different modeling approaches, data sources, and estimation techniques (and those differences have important implications for policymakers), there does appear to be some convergence in their findings. A number of tentative conclusions seem apparent:

(1) The short-run elasticity of the total demand for gasoline is low; the statistically significant estimates presented range from -0.11 to -0.47 but cluster around -0.2.

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(2) The short-run elasticity of private automobile demand for gasoline may be higher than the elasticity of total demand; the findings of Ramsey et al., Data Resources, Inc., and Chase Econometric Associates support this conclusion. This result seems plausible since private automobile demand is likely to be more discretionary than either commercial or off-the-highway fuel demand.

(3) There is less agreement about long-run price elasticity, but several estimates have been in the range of -0.65 to -0.85.

(4) Estimates of the time required for full adjustment to a price change vary widely. The Data Resources, Inc. quarterly model indicates a fairly rapid adjustment—10 quarters or 2.5 years. Models estimated with annual data generally imply much longer time periods (Houthakker and Kennedy, 5 years; McGillivray, 10 years; Sweeney, 12 years).

**ANALYSES**

Much past empirical work on the demand for highway fuel has lacked a strong analytic basis. Some researchers appear to have simply regressed highway fuel use against what appeared to be a reasonable set of independent variables. When an analytic basis is lacking, it is sometimes hard to know what the empirical results mean.

We wanted to provide a strong analytic basis for our empirical results. To do so, we developed the short-run demand model presented in this section. We also derived relationships between the demand for vehicle miles and the demand for highway fuel. These relationships allow us to estimate how much vehicle miles traveled will change when fuel use changes.

**Travel as Household Production**

Most automobile vehicle miles are "produced" by families. Except for taxi services, families do not "buy" vehicle miles in the same sense that they buy furniture. Rather, they buy the required goods
and services and produce vehicle miles. To represent this produ-
don process, we use a simplified model of family behavior.
In the short run, a family brings together three inputs to produce
vehicle miles. One is vehicle services (A)—the use of a vehicle
for a period of time. In the short run, the quantity of vehicle
services available to the family is assumed to be fixed; indeed,
this condition defines the short run. The two other inputs are
fuel (F) and travel time (T_v). Of course, quantities of inputs
besides fuel and travel time can be changed in the short run;
maintenance services are an example. (We limit our analysis to
two variable inputs for simplicity.) We can then write a short-
run production function for vehicle miles traveled (V) as:

\[ V = [F, T_v; A] \]

We assume this short-run production function both is homothetic
in the variable factors and has constant returns to scale.

To keep our analysis simple, we assume that a family con-
sumes only one other good (G), which it also produces by combin-
ing a purchased input (H) and time (T_g). The family's production
function for the other good can be written as:

\[ G = G[H, T_g] \]

---

9 Note that we treat all automobiles alike. Doing so makes the
analysis much easier; we can handle it with the available data. How-
ever, it would be preferable to have treated vehicle miles driven in
different kinds of automobiles as different goods. Automobiles may
be described by their age, fuel efficiency, interior room, and other
features. If we could have treated them separately, we would have
allowed for another adjustment that families could make to changed
gasoline prices. Families that own two or more cars with different
fuel efficiencies can adjust to changes in gasoline prices by using
a particular automobile more or less frequently. While this modelling
limitation may not be of great importance for our short-run work, it
becomes more serious when long-run automobile stock adjustments are
considered.
Let $U_1$ be an index of the satisfaction the family derives from consuming vehicle miles and the other good, or

$$U = U \left\{ V[F,T,v; A], G[H,T,g] \right\} \quad (2.2)$$

We assume that a family maximizes its satisfaction subject to the constraint that its "full" expenditures equal its "full" income; i.e.,

$$F F_f + T W + A P_a + H P_h + T W = \bar{T} W + Y \quad (2.3)$$

where $F_f$ = the price of fuel per gallon
$W$ = the wage rate
$P_a$ = the rent price of vehicle services
$P_h$ = the price of the other purchased input
$\bar{T}$ = total time available for family production and work
$Y$ = nonwage income.

We partially differentiate Eq. (2.2) subject to Eq. (2.3) with respect to each input's quantity except vehicle services, which is assumed fixed, and the Lagrangian multiplier. The resulting set of equations can be solved for the input quantities in terms of their prices, the wage rate, time available for family production and work, income from wealth, and the value of vehicle services. Specifically, the equation for highway fuel can be written as:

$$F = F(P_f, W, P_h, \bar{T}, Y, A P_a) \quad (2.4)$$

or, normalizing on $P_h$,

$$F = F\left( \frac{P_f}{P_h}, \frac{W}{P_h}, \frac{\bar{T}}{P_h}, \frac{Y}{P_h}, \frac{A P_a}{P_h} \right) \quad (2.5)$$
where

\[ \frac{\partial F}{\partial (P_f | P_h)} < 0 \]

\[ \frac{\partial F}{\partial (W | P_h)} > 0 \]

\[ \frac{\partial F}{\partial (Y | P_h)} > 0 \]

The sign of \( \frac{\partial F}{\partial (AP_a | P_h)} \) could be either plus or minus. We expect more vehicle services to lead to greater highway fuel use. However, the variable is the product of vehicle services and their rent price. If vehicle services are a complement to highway fuel in the production of vehicle miles, then the relationship between their rent price and highway fuel use would be negative. If they are substitutes, it would be positive. Since we are not sure about this sign, we cannot say whether the sign of the overall derivative is plus or minus.

The above relationship is our basic demand curve for highway fuel. In the subsections below, lack of data and other empirical difficulties will cause us to slightly modify this demand curve. However, we will proceed to set out our conceptual approach as though we could estimate it.

In the short run, a family can decrease its fuel consumption in two ways. First, it can drive less; we term the resulting reduction the scale effect. Second, it can substitute travel time for fuel by changing its driving habits; this substitution could be made by driving slower. We term that resulting reduction the substitution effect; it means that miles per gallon of fuel \((M)\) must increase. The substitution effect can be expressed in functional form:

\[ M = M(P_f | P_h, W | P_h, C_1, \ldots, C_m) \quad (2.6) \]
Here, $C_1, ..., C_m$ stands for the characteristics of the driving environment and automobile stock. If we assume a linear homogeneity and a constant wage rate, this function summarizes the substitution of time for fuel when the number of automobile miles driven by the family is unchanged.\(^{10}\)

We want to distinguish between the scale effect and the substitution effect in our fuel demand equation. We can do so by putting miles per gallon of fuel used into Eq. (2.5). We now have

$$F = F \left[ \frac{P_f}{P_h}, \frac{P_f}{P_h}, ..., \right]$$

where the total impact of a change in the real price of fuel has two components:

$$\frac{\partial F}{\partial \left( \frac{P_f}{P_h} \right)} = \left. \frac{\partial F}{\partial \left( \frac{P_f}{P_h} \right)} \right|_{M=C} + \left. \frac{\partial F}{\partial M} \right|_{\frac{P_f}{P_h} = C} \cdot \frac{dM}{d \left( \frac{P_f}{P_h} \right)} \quad (2.7a)$$

Scale Effect  Substitution Effect

Below we focus on the effect on fuel use of changes in fuel price. For the moment, to make the notation less complex, we will write the fuel use and miles per gallon relationships without the other variables. Also, we will drop $P_h$; for the rest of this report, the monetary variables will be in real terms.

Relationships Between Elasticities of Fuel Use and Vehicle Miles Traveled

Before turning to our statistical methodology and results, it is useful to derive some relationships between price elasticities of fuel use and vehicle miles traveled. We do so for two reasons. First, we can then estimate the effects of changes in fuel price on both vehicle miles traveled and fuel use. The second reason involves the data that were available for our study. At the national level, two data series were available to measure automobile fuel use: a direct measure, gallons of fuel consumed; and an indirect measure, automobile vehicle miles traveled. As discussed below, we were not certain which data series contained the fewest errors. These relationships also allow us to compare the results obtained from estimating equations using the two data series.

By definition, vehicle miles traveled per household is equal to fuel use multiplied by miles per gallon or,

\[ V \equiv F[P_f, M(P_f, \ldots), \ldots] \cdot M(P_f, \ldots) \]

We use this identity to derive the following relationships (see App. B for details). The symbol 'E' denotes elasticity; for example, \( E^F_{P_f} \) is the total elasticity of fuel use with respect to fuel price. Partial elasticities are denoted with a vertical base; thus, \( E^F_{P_f} \big|_{M=C} \) is the partial elasticity of fuel use with respect to fuel price, holding miles per gallon constant. For our purposes, the important results are:

1. Holding miles per gallon constant, the elasticity of vehicle miles with respect to fuel price equals the elasticity of fuel use with respect to fuel price, or:

\[ E^V_{P_f} \big|_{M=C} = E^F_{P_f} \big|_{M=C} \];

(2.8)
2. Holding fuel price constant, the elasticity of vehicle miles with respect to an autonomous change in miles per gallon equals the elasticity of fuel use with respect to an autonomous change in miles per gallon plus 1, or:

\[ \left. E_M^V \right|_{P_f=C} = \left. E_M^F \right|_{P_f=C} + 1; \quad (2.9) \]

3. The total elasticity of vehicle miles with respect to fuel price equals the elasticity of fuel use with respect to fuel price, holding miles per gallon constant, plus the elasticity of fuel use with respect to miles per gallon (holding fuel price constant) plus 1, multiplied by the elasticity of miles per gallon with respect to fuel price, or:

\[ E_P^V = E_P^F \left|_{M=C} + \left( E_M^F \left|_{P_f=C} + 1 \right. \right) \cdot E_P^M \right. \quad (2.10) \]

In Eq. (2.10) the total elasticity of vehicle miles traveled with respect to fuel price is seen to be the sum of two offsetting effects. The first term represents the scale effect. The second term represents the substitution effect; when \( P_f \) rises, miles per gallon (\( M \)) increases as households substitute time and other inputs for fuel. Thus, the price per mile of driving declines, partially offsetting the scale effect.

4. The total elasticity of fuel use with respect to its price also contains two terms:

\[ E_P^F = E_P^V \left|_{M=C} + \left( E_M^V \left|_{P_f=C} - 1 \right. \right) \cdot E_P^M \right. \quad (2.11) \]

5. The elasticity of vehicle miles with respect to fuel price, holding miles per gallon constant, equals the negative of the elasticity of vehicle miles with respect to miles per gallon, holding fuel price constant, or:
In other words, either an increase in the price of fuel, or a decrease in miles per gallon that has the same impact on the price of fuel per mile, will have the same effect on vehicle miles driven.

**Implications for Empirical Work**

Our basic gasoline demand function is given in Eq. (2.5). Below we present estimates of the gasoline demand function using two data sets. We will express it in loglinear form because that form yields direct estimates of elasticities. Thus, we can use the relationships derived above to easily interpret and compare our results. Since our goal is to provide some insights into the relative sizes of different adjustment processes, in our short-run analysis, we attempt to measure the size of the scale and substitution effects.

Unfortunately, simply estimating Eq. (2.5) does not provide estimates of both the total short-run price elasticity of motor fuel and its components. We can write Eq. (2.5) with or without the miles per gallon variable \( M \); we can exclude \( M \) on the grounds that it is itself a function of the fuel price. Of course, whether miles per gallon is included or excluded will make a difference in how we interpret our results. However, neither way of estimating Eq. (2.5) provides estimates of both the total short-run price elasticity and its components.

If we include \( M \), the loglinear form of Eq. (2.5) is

\[
LF = a + E_{\frac{P}{M}}^F \left|_{M=C} \right. \cdot LP_{\frac{P}{M}}^F \left|_{P_{f}=C} \right. \cdot LM + \ldots 
\]

The coefficients of fuel price and miles per gallon are the partial elasticities, holding the other variable constant. For example, the coefficient of fuel price is the elasticity of fuel use with respect to its price with miles per gallon fixed. The reason is that, when \( M \) is in the equation, we are already accounting for any variations in fuel use due to variation in miles per gallon. The coefficient of \( LP_f \), can reflect only the direct effects of changes in fuel price on fuel use.
Thus, this coefficient provides an estimate of the scale effect discussed above; the variation reflected in this coefficient can only be due to variation in miles traveled. For similar reasons, the coefficient of LM must be interpreted as the elasticity of fuel use with respect to miles per gallon when the fuel price is fixed.\footnote{Note that Eqs. (2.9) and (2.12) imply a restriction on the coefficients of $LP_f$ and LM; i.e.,
\[ E_M^{LF} \bigg|_{P_f} = C = - (1 + E_P^{LF} \bigg|_{M=C}) \]}

The difficulty with this form of the equation is that it does not provide an estimate of the total short-run elasticity of fuel use with respect to its price. As can be seen from Eq. (2.12), a third element is needed: the elasticity of miles per gallon with respect to fuel price. We can estimate that element if we assume a constant elasticity of substitution between fuel and travel time for the production of vehicle miles in the short run.\footnote{K. J. Arrow et al., "Capital Labor Substitution and Economic Efficiency," \textit{Review of Economics and Statistics}, Vol. 43, No. 3, August 1961, pp. 229-230.} We need estimate only the following relationship:

\[ LM = c + E_M^{LF} LP_f + \ldots \]  \hspace{1cm} (2.16)

where $c$ is the intercept.\footnote{As will be discussed below, this approach introduces simulta-} From here on, we will treat Eq. (2.16) as an aggregate relationship. It will be estimated with aggregate data; i.e., the miles per gallon figures are obtained by dividing total vehicle miles by total highway fuel use.\footnote{As will be discussed below, this approach introduces simulta-}

As an alternative to Eq. (2.14), we can estimate an equation that does not have miles per gallon as an independent variable. It is

\[ LP = b + E_P^{LF} LP_f + \ldots \]  \hspace{1cm} (2.17)

where $b$ is the intercept. Here the coefficient of fuel price is the...
total elasticity of fuel use with respect to fuel price. It is the
total elasticity because, with the miles per gallon variable out of
the estimating equation, the coefficient of $LP_f$ reflects not only the
direct variation of fuel use with fuel price, but also the indirect
variation through changes in miles per gallon.

The problem with Eq. (2.17) is opposite to the one with Eq. (2.14).
Here we have an estimate of the total elasticity of fuel use with re-
spect to fuel price, but no breakdown by components. We can derive the
components, however; to do so, we need an independent estimate of the
elasticity of miles per gallon with respect to fuel price; again, we
can get an estimate with Eq. (2.16). With estimates of the total
elasticity of fuel use with respect to fuel price and the elasticity
of miles per gallon with respect to fuel price, we can use Eqs. (2.8),
(2.9), (2.11), and (2.12) to derive the component elasticities. 15

The relationships between elasticities derived above also allows
us to imply values for the elasticities of fuel consumption using data
on vehicle miles traveled. We can estimate the following equation:

$$LV = d + E^V_F LP_f + ...$$  (2.18)

where $d$ is the intercept. If we use Eq. (2.16) to get an estimate of
the elasticity of miles per gallon with respect to fuel price, we can
then use Eqs. (2.8), (2.11), and (2.12) to imply values for the total

14 S. Schim van Loeff and R. Harkema, "A Note on Aggregation of
CES-Type Production Functions," Netherlands School of Economics, un-
published paper, n.d.

15 To go from Eqs. (2.17) and (2.16) to Eq. (2.14), we need to do
more than derive the component elasticities. We also need to derive
a new intercept term. After a long algebraic derivation, with which
we will not burden the reader, we find that the relationship between
intercept terms is

$$b = E^F_M c.$$
and component elasticities of motor fuel.\textsuperscript{16}

In sum, we can compute values for all the elasticities using the mathematical relationships presented above and estimates of any one of the following combinations of elasticities:

- A total fuel price elasticity and the elasticity of miles per gallon with respect to fuel price.
- A component elasticity and the elasticity of miles per gallon with respect to fuel price.
- A total fuel price elasticity and a component elasticity.

Thus, these relationships allow us to compare elasticity estimates made using different estimating equations and data sets.

\textbf{Supply Considerations}

Observed data on fuel prices and consumption reflect the intersection of demand and supply at each point in time. Therefore, to properly estimate the demand equation, it is necessary to make explicit the relationship between the demand and supply functions. We make the simplifying assumption that, during the period our data cover (1950-1972), the supply is infinitely elastic at the prevailing price and, therefore, independent of the level of demand.\textsuperscript{17} This assumption is consistent with the idea that within a one-year period the total annual supply of crude oil and the prices of distillates other than motor fuel are exogenous to the gasoline market.

\textsuperscript{16}The intercept term would also have to be adjusted. The adjustment is

\[ a = d - \frac{\hat{V}}{\hat{M}}. \]

\textsuperscript{17}With one exception, all previous research appears to also adopt this assumption. The exception is Ramsey, Rasche, and Allen, op. cit., who provide a model of gasoline demand and supply in which fuel consumption and prices are endogenously determined.
EMPIRICAL RESULTS USING POOLED STATE TIME-SERIES DATA

Equation Specification and Data

The fuel demand equation (2.5) was altered for estimation with state time-series data. Lack of a consistent measure of the wage rate variable for individual states prevented its inclusion. The wage and nonwage income variables were replaced by a single proxy variable measuring personal disposable income; the estimating equation then took two forms (with log values indicated by L):

\[
LF = \alpha_0 + \alpha_1 LP_f + \alpha_2 LY + \alpha_3 LA + \beta_1 \text{ (UPOP, PT)}
\]

\[
LF = \alpha_0 + \alpha_1 LP_f + \alpha_2 LY + \alpha_3 LA + \alpha_4 LM + \beta_1 \text{ (UPOP, PT)}
\]

where \( Y \) = personal disposable income per capita,

\( \text{UPOP} \) = percent of state population residing in urban areas,

\( \text{PT} \) = percent of total vehicles registered as trucks or buses,

and all other variables are defined as above.

Fuel consumption (\( F \)) data were obtained from Federal Highway Administration (FHWA) publications; they are for motor fuels used to operate vehicles on the highways.\(^{18}\) These data include gasoline and other fuels (such as diesel fuel) so long as they are used on highways. Data on gasoline prices (\( P^*_f \)) were obtained from Platt's Oil Price Service; they represent the average annual price of regular gasoline (including taxes) and cover at least one city in each of the 48 contiguous states. Disposable personal income (\( Y \)) data by state were obtained through 1968 from Survey of Current Business, April 1969; similar income data for 1969-1970 were extrapolated by applying the ratio of state disposable/personal income in 1968 to state personal income data for 1969 and 1974. Vehicle registrations (\( A \)) by state were taken from FHWA publications and include passenger cars (private plus publicly owned), trucks, buses, and motorcycles. The percent of state population residing in urbanized areas (\( \text{UPOP} \)) was obtained from the U.S. Statistical Abstract, 1952-1970. Prices and income were de-

flated by the national consumer price index for total consumption compiled by the Bureau of Labor Statistics of the Department of Labor.

The one variable for which standard data are not readily available is average auto or vehicle efficiency by state. To construct the data for this variable (M), we used an unpublished 1970 FHWA survey of state highway departments' procedures for calculating vehicle miles of travel. In this survey, states were asked to estimate the average miles per gallon for all vehicles registered in their state during 1970. Approximately half of the states did so by dividing estimated vehicle miles of travel by total fuel consumption during 1970. Most of the other states developed independent estimates based on historical consumption rates obtained from surveys of vehicle users. Seven states simply used a nationwide average developed by the FHWA. 19 The state data on fuel efficiency for 1970 were then extrapolated backward to create estimates for 1955-1969. The extrapolation technique used was to calculate the ratio of a state's MPG (1970) to the FHWA national average MPG and then apply this ratio to FHWA historical data on average U.S. miles per gallon. 20 This technique is crude and probably involves some inaccuracies. 21 As will be seen below, however, the empirical results seem reasonable and it therefore seems defensible to use the data.


20 That is, for each state:

\[ SMPG_{i} = \frac{SMPG_{70}}{USMPG_{70}} \times USMPG_{i} \]

where \( SMPG_{i} \) = average state fleet miles per gallon in year \( i \)

\( USMPG_{i} \) = average U.S. fleet miles per gallon in year \( i \).

21 Specifically, if the composition of a state's vehicle fleet has shifted radically over time compared with the national average, this approach will tend to produce biased estimates. For example, if a state but not the nation experienced a rapid shift from large to small passenger cars, the shift would lead to an underestimate of the state's average miles per gallon. Although that sort of shift may have occurred in areas
Estimation Problems

Generalized Least Squares. We used a pooled time-series (1955-1970) of cross-sectional state data to estimate the motor fuel demand equation. This type of data has the advantage of increasing the variation in gasoline consumption per capita and in real price of gasoline compared with aggregate national time-series data; it is an advantage because, it is to be hoped, greater statistical precision will result. When mixed state cross-sectional time-series data are used, however, the usual assumption regarding the serial independence of the error terms is likely to be violated. In our case, it is likely that individual state effects will be present in the data; as a result, estimation using ordinary least squares will yield inefficient estimates of the model coefficients.

To indicate the nature of the problem and a proposed solution, consider the following model:

\[ y_{it} = \alpha + \beta x_{it} + u_{it}, \quad (i = 1, \ldots, 48 \text{ states}) \]
\[ t = 1, \ldots, 16 \text{ years} \]

where \( y_{it} \) is the dependent variable, \( \alpha \) is a constant term, \( \beta \) is a 1 by \( k \) vector of coefficients to be estimated, \( x_{it} \) is a vector of \( k \) independent variables and \( u_{it} \) is the disturbance term. The \( u_{it} \) is included to represent individually unimportant influences either omitted from the analysis or arising from measurement error. A number of assumptions concerning the stochastic structure of the disturbance terms are possible.\(^{22}\) For this study we adopt a version of the error components model that assumes the following structure of the \( u_{it} \)'s:\(^{23}\)

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\(^{22}\) For a complete discussion of the various assumptions concerning the error structures when pooled cross-section time-series data are used, see J. Kmenta, *Elements of Econometrics*, The MacMillan Company, New York, 1971.

\[ u_{it} = u_i + v_{it} \]
\[ E(u_{it}) = 0 \text{ for all } i \text{ and } t, \]
\[ E(u_{it}^2) = c^2, \quad i = i', \; t = t'; \]
\[ E(u_{it} u_{i't'}) = \begin{cases} c^2 & \text{, } i = i', \; t \neq t'; \\ c^2 & \text{, otherwise} \end{cases} \]

In ordinary words, this model of disturbances divides each \( u_{it} \) into two statistically independent parts: \( u_i \), a time-invariant individual state effect and a remainder, \( v_{it} \). Both \( u_i \) and \( v_{it} \) are assumed to be independently distributed with zero means. In addition, serial dependence is postulated between the \( u_{it} \)'s for a given state over time, but not between different states. (As Balestra and Nerlove (1966, p. 595) noted, this second assumption is somewhat dubious where the states are geographically determined by arbitrarily drawn boundaries, as is the case here.)

Under these assumptions, when the observations are arranged by states over time, the variance-covariance matrix of the disturbances is:

\[
E(u_{it} u_{i't'}) = c^2 \begin{bmatrix} A & 0 & \ldots & 0 \\ 0 & A & & \\ \vdots & & \ddots & \\ 0 & \ldots & & A \end{bmatrix}
\]

where:

\[
\begin{bmatrix} 1 & p & \ldots & p \\ p & 1 & \ldots & \vdots \\ \vdots & \ddots & \ddots & \vdots \\ p & \ldots & & 1 \end{bmatrix}
\]

The parameter \( \rho = \frac{c^2}{\sigma^2} \); it is the proportion of residual variance accounted for by time-invariant state effects. Nerlove has shown that estimation using generalized least squares for the model with the above variance-covariance matrix may be accomplished by a two-round procedure. \(^{24}\) The first stage estimates \( \rho \) based upon a regression equivalent to including the independent variables plus an indi-

\(^{24}\) The actual estimation technique employed here is discussed at length in Nerlove and Schultz, op. cit.
individual constant term for each state. This first stage actually estimates \( \rho \) using the deviations from the individual state means. The second round then yields coefficient estimates based on transformed observations; these estimates are referred to as generalized least squares (GLS) estimates.

**Simultaneous Equations Bias.** When we specify the demand equation with a miles per gallon variable included, the resulting estimates of the coefficients will be biased to some unknown degree because of simultaneous equations bias. To see this, consider the following simplified version of our model: \(^{25}\)

\[
V_t = \alpha + \beta P_t + \gamma M_t + u_t
\]

\[
M_t = \frac{V_t}{F_t} = \frac{V_t}{F_t^{\frac{1}{\gamma}}} \text{ by definition}
\]

In this system \( V, F, \) and \( M \) are taken as endogenous, while \( P \)--the price of fuel--is exogenous or determined outside the model. We make the usual assumptions regarding \( E(u_t) \) and \( E(u_t^1) \) and the independence of \( P_t \) and \( u_t \). However, for the valid application of the least squares estimation technique, there remains the question of the independence of \( M_t \) and \( u_t \) in the first equation. Substitution of the first equation into the second yields:

\[
M_t = \frac{\alpha}{F_t^{\gamma}} + \frac{\beta P_t}{F_t^{\gamma}} + \frac{u_t}{F_t^{\gamma}}
\]

so that \( M_t \) is, in general, affected by \( u_t \). Furthermore,

\[
E \{ u_t [M_t - E(M_t)] \} = \frac{1}{F_t^{\gamma}} E(u_t^2) \neq 0
\]

so that the disturbance terms \( (u_t) \) and \( M_t \) are correlated and estimates of \( \gamma \) will be biased using OLS. The direction of bias is upward so that for \( \gamma \) less than zero the bias is toward zero.

\(^{25}\) This discussion follows that of Johnston (1963), pp. 231-234.
In our empirical work, we estimated the pooled state cross-section time-series model using the method of two-stage least squares; the results were unsatisfactory because several of the coefficient estimates proved unstable. In our national time-series model, we excluded the miles per gallon variable from the estimating equation because of problems of collinearity; we therefore made no attempt to apply simultaneous equation techniques to this model.

**Empirical Results**

The basic gasoline demand equation was estimated with and without the miles per gallon (M) variable. The logarithmic values of gasoline consumption, gasoline price, income, vehicle registration, and miles per gallon were used; this allows us to read the estimated coefficients as elasticities. Two additional variables were entered linearly to control for differences in motor fuel consumption due to differences between states in urbanization and vehicle fleet mix. The two variables measure, respectively, the percent of state population residing in urban areas (UPOP) and the percent of total state vehicles registered as trucks (PT).

Equations 1 and 2 in Table 2 display the results obtained when the miles per gallon variable is excluded. The GLS estimates of the price elasticity are quite similar; they average -0.26. As discussed earlier, these are estimates of the total short-run price elasticity; thus, they include adjustments in vehicle miles driven and average miles per gallon to a change in fuel price. Equations 3 and 4 present the estimated equation results with the miles per gallon variable, using OLS and GLS respectively. In both equations the coefficient of price is lower, averaging -0.22. The OLS estimate of the elasticity of fuel consumption with respect to miles per gallon is -0.64, an intuitively plausible value. However, the GLS estimate of this elasticity is -1.9, about three times as large as that obtained using the technique of OLS. This value is unreasonably large in view of our theoretical results.  

\[ E_p \left| M=C \right| + E_m \left| P=C \right| = -1 \]

26From our theoretical model we expect that \( E_p \left| M=C \right| + E_m \left| P=C \right| = -1 \). Using a standard t-test we can test our regression results to see if this relationship holds in the statistical sense. The regression co-
Table 2

REGRESSION RESULTS USING POOLED STATE TIME-SERIES DATA
(Independent Variable: Log of Fuel Consumption Per Capita)

<table>
<thead>
<tr>
<th>Estimation Technique</th>
<th>L(P)_{f}</th>
<th>L(Y/POP)</th>
<th>L(M)</th>
<th>L(A/POP)</th>
<th>UPOP</th>
<th>PT</th>
<th>Constant</th>
<th>R^2</th>
<th>ρ</th>
<th>Degrees of Freedom</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. GLS</td>
<td>-0.27</td>
<td>0.18</td>
<td>--</td>
<td>0.93</td>
<td>-0.09</td>
<td>--</td>
<td>-0.66</td>
<td>.95</td>
<td>.91</td>
<td>763</td>
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<td>(9.5)</td>
<td>(42.3)</td>
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<tr>
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<td>-0.25</td>
<td>0.18</td>
<td>--</td>
<td>0.92</td>
<td>--</td>
<td>0.36</td>
<td>-0.86</td>
<td>.95</td>
<td>.90</td>
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<td>(9.4)</td>
<td>(39.3)</td>
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<td>(4.7)</td>
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<tr>
<td>3. OLS</td>
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<td>0.08</td>
<td>-0.64</td>
<td>0.84</td>
<td>--</td>
<td>0.15</td>
<td>1.3</td>
<td>.83</td>
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<td>762</td>
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<td></td>
<td>(1.8)</td>
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<td>4. GLS</td>
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<td>--</td>
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<td>0.80</td>
<td>--</td>
<td>0.21</td>
<td>3.8</td>
<td>.96</td>
<td>762</td>
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<td>0.29</td>
<td>0.94</td>
<td>.95</td>
<td>.90</td>
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<td>(10.4)</td>
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<td>(6.2)</td>
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</table>

NOTES:

t-statistics in parentheses. Using a two-tailed test, t-statistics exceeding 2.38 (5 percent significance level) are sufficient to reject the hypothesis that the estimated coefficient is equal to zero.

-- indicates that variable was excluded from estimating equation.

\textsuperscript{a}Coefficient derived from equality condition: elasticity of fuel consumption with respect to price plus elasticity of fuel consumption with respect to efficiency equals one, e.g., \(-1 = \frac{E_{Pf}}{E_{Pf}} + \frac{E_{M}}{E_{M}}\) or \(E_{M} = -0.78\).
Neither Eq. 3 nor 4 is entirely satisfactory; the OLS equation lacks the statistical precision obtained by using GLS, while the GLS equation does not agree with our a priori expectations regarding the elasticity of fuel use with respect to miles per gallon. To improve upon this situation we adopted a third estimation procedure to obtain Eq. 5. In effect, the null hypothesis that $E_{pf}^F + E_M^F = -1$ was incorporated into the estimation procedure by rewriting the fuel demand equation as:

$$\log F = a + E_{pf}^F \cdot \log p_f + (-1 - E_{pf}^F) \cdot \log M + ...$$

or, combining terms,

$$\log F + \log M = a + E_{pf}^F \cdot (\log p_f - \log M) + ...$$

Estimation of this equation—using GLS—of $\hat{Y}$ ($= \log F + \log M$) as the dependent variable and $\hat{X}$ ($= \log p_f - \log M$) as an independent variable yielded the results shown in Eq. 5. The price coefficient of -0.22 is almost identical to the Eq. 4 estimate (-0.23), while the derived value of $E_M^F = -0.78$ is somewhat greater than the Eq. 3 estimate.

The coefficients from Eq. 3, Table 2, are: $E_{pf}^F = -0.21$ and $E_M^F = -0.64$. The appropriate t-statistic for this test is

$$t = \frac{E_{pf}^F + E_M^F - (-1)}{\sqrt{\text{Var}(E_{pf}^F) + \text{Var}(E_M^F) + 2\text{COV}(E_{pf}^F, E_M^F)}}$$

For the coefficients of Eq. 3 (OLS) the calculated t-statistic is 1.3 while for Eq. 4 (GLS) the statistic is 8.5. With 762 degrees of freedom and using a two-tailed test, a t-statistic of 2.68 is necessary to reject the null hypothesis (at the 1 percent level of significance) that $E_{pf}^F + E_M^F = -1$. Thus our OLS results lead us to accept the null hypothesis while the GLS results lead to the opposite conclusion.
of the miles per gallon coefficient.

Comparison of Price Elasticity Estimates

The regression results presented above allow us to calculate total price elasticity in two separate ways. The price coefficients from Eqs. 1 and 2 provide a direct estimate of this elasticity; the average value from these two equations is -0.26. The second procedure uses the equation results from Eq. 5, in which the price coefficient represents a partial elasticity—the effect of price on consumption, holding fuel efficiency constant. To obtain an estimate of the total price elasticity we need a value for the second term $E^M_P$ in the total elasticity equation:

$$E^F_P = E^F_P \mid_{M=C} + E^F_P \mid_{M=C} \cdot E^M_P$$

Using the regression coefficient from Eq. 5, Table 1, yields:

$$E^F_P = -0.22 + (-0.78) \cdot E^M_P$$

To calculate the total $E^F_P$ we need an estimate of $E^M_P$. We obtained it from a separate equation relating the fuel efficiency variable to price. The estimated equation using GLS is:

$$LM = 2.2 + 0.058 \text{LP}_f - 0.001LY - 0.06PT$$

\[ (21.2) \quad (11.2) \quad (-3.8) \quad (-1.9) \]

$$\bar{R}^2 = 0.30 \quad \text{DF} = 762$$

Using the value of 0.058 for $E^M_P$, yields an estimate of $E^F_P = -0.22 - 0.045 = -0.265$. This value is almost identical to that obtained by estimating $E^F_P$ directly, i.e., by excluding the miles per gallon variable from the regression equation.

All the estimated coefficients of vehicle registrations per capita fall between 0.80 and 0.93, a range resembling the estimates presented by Chase Econometrics using national time-series data to
explain V. The value of these estimates indicates that as households increase the number of vehicles they own, they drive fewer miles per vehicle.

All of the GLS estimates of income elasticity are 0.18, a value substantially less than estimates obtained in previous research using flow adjustment models. 27 In our data, per capita vehicle registration is highly correlated with per capita income; and this may explain our lower estimate of short-run income elasticity, since in prior research the income variable has partially captured the effects of vehicle ownership on fuel use.

Finally, we note that in all of the GLS equations the estimated proportion of residual variance, $\hat{\rho}$, accounted for by time-invariant state effects is very large, 90 to 97 percent. This indicates that, in the present study, controlling for state-specific effects when using pooled cross-sectional data is important to obtain maximum statistical precision.

EMPIRICAL RESULTS USING NATIONAL TIME-SERIES DATA

We are especially interested in fuel used and miles traveled in automobiles. 28 Data at the state level do not break out fuel use and vehicle miles traveled by type of vehicle, i.e., autos, buses, trucks. We know of such data only at the national level. Consequently, we also estimated the short-run model using national time-series data for automobiles.

National time-series data provide fewer data points. When using those data, we are trading off the greater statistical reliability that goes with many data points for the ability to focus on automobile gasoline use and travel.

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27 One-year income elasticities reported in other research are: 0.6 (Data Resources, Inc.), 0.74 (Houthakker and Kennedy, OECD model), 0.58 (L. Phifps).

28 In our description of results using national time-series data, the symbol "F" refers to gasoline used by automobiles and the symbol "V" refers to miles traveled in automobiles.
Model Modifications

Recall that our gasoline demand equation is the following:

$$F = F(P_f, W, \bar{T}, Y, AP_a)$$

where $P_f$ = the price of gasoline per gallon deflated by a measure of nontransportation price

$W$ = deflated average wage rate per hour

$\bar{T}$ = time available for household production and work

$Y$ = deflated nonwage income

$AP_a$ = deflated value of auto services

We also specified a miles per gallon equation:

$$M = M(P_f, W, C_1, \ldots, C_m)$$

where $C_1, \ldots, C_m$ stand for characteristics of the driving environment and automobile stock. We can also write a vehicle miles demand relationship:

$$V = V(P_f, W, \bar{T}, Y, AP_a)$$

Above we showed that either Eqs. (2.16) and (2.17) or Eqs. (2.16) and (2.18) could be used to derive the following equation:

$$F = F[P_f, M(P_f, W, C_1, \ldots, C_m), W, \bar{T}, Y, AP_a]$$

This equation allows us to derive our short-run (substitution and scale) effects. Here we will estimate Eqs. (2.16), (2.17), and (2.18) and then derive equation (2.14).

Data limitations and other problems required a number of changes in the equations. We assumed that the available time for household production and work ($\bar{T}$) is constant; it would change only if Americans' sleeping habits changed. If it is constant, it cannot account for the
variations in automobile gasoline use; therefore, we dropped \((T)\) from the equation. We also dropped nonwage income \((Y)\), for which data are unavailable. Finally, we had to substitute the automobile stock \((A)\) for the value of automobile services \((AP_a)\). With these changes, Eq. (2.5) becomes

\[
F = F(P_f, W, A)
\]

We did not succeed in getting good estimates for this equation. The wage coefficient was never of high statistical significance, perhaps because of the high correlation between wage rates and automobile ownership in our data. Instead, we used two alternative forms:

Form A: \(F = F(P_f, A)\)
Form B: \(F = F(P_f/W, A)\)

With the first form, we drop the wage rate \((W)\); this has the disadvantage of introducing further specification error. In the second, we use the ratio of fuel price to the wage rate. In so doing, we introduce a restriction, i.e., the effect of a change in the average wage rate is restricted to the same value as, but of opposite sign to, the effect of a change in gasoline prices.

We also want to account for changes in characteristics of the driving environment and automobile stock. One change we want to account for was due to federal emission and safety standards, the first of which were introduced in 1968. We used a "dummy" variable \((D)\) to account, at least crudely, for the standards. It is set equal to zero in 1967 and before; it is equal to one for 1968 and after.

In the short run, the type of automobiles on the road will constrain how Americans can cut down their gasoline consumption by changing their driving habits. To account for the constraints, we include average auto miles per gallon last year \((M_{t-1})\) as an independent variable.

We also found that adding the unemployment rate \((Z)\) as an indepen-
dent variable improved the miles per gallon equation. Within the context of our analysis, this makes sense if the average wage rates do not fully reflect the value Americans place on their time. The average wage rate is relevant only to Americans who are working; the unemployed might value their time less.

With these changes, the miles per gallon equation can be written as:

\[ M = M(P_f, W, Z, M_{t-1}, D) \]

We did not succeed in estimating this equation; the coefficients of the wage variable were not statistically significant. Instead, we used two alternative forms:

Form A: \[ M = M(P_f, Z, D) \]
Form B: \[ M = M(P_f/W, Z, M_{t-1}, D) \]

In the first form, we drop the wage rate; this introduces additional specification error. In the second form, we restrict the impact of changes in the wage rate on miles per gallon to be the same size as, but of opposite sign to, the effect of changes in gasoline price.

We normalize automobile gasoline use \( (F) \), automobile miles driven, and automobile ownership for three bases: total population \( (\text{POP}) \), driving age population \( (\text{DPOP}) \), and households \( (H) \). When we started this research, we normalized only on households. We added population and adult population for two reasons. First, we wanted to make our results more comparable to results obtained by others; most other work has normalized on total population. Second, we noticed an increase beginning about 1963 in the growth rates of automobile gasoline use and miles traveled. At that time, the driving age population (aged 18 to 65) changed from a declining to an increasing proportion of total population. One way to account for this trend change is to normalize with driving age population.

Data. Our data for automobile gasoline use \( (F) \), automobile miles
driven (V), and automobile ownership (A) come from *Highway Statistics*. Before 1964, this source gives one estimate for both automobiles and motorcycles. To take out gasoline used and miles traveled by motorcycles, we assumed that the average motorcycle traveled 3900 miles a year and averaged 50 miles per gallon. These values are averages for 1964 to 1972.

We normalized on population (POP), driving age population (DPOP), and households (H). Actual values (for census years) and estimates for these variables are from the U.S. Bureau of the Census's *Current Population Reports*. Data on average wages in manufacturing (W) and unemployment rates (Z) are from the *Economic Report of the President*, February 1972.

We used the gasoline price component of the national Consumer Price Index (Pf) to measure gasoline price. We changed this series from nominal to relative prices by using a deflator; the deflator is the national Consumer Price Index with its private and public transportation components removed.29 We removed them because the model calls for the price of gasoline relative to a measure of the prices of other goods and services; see Eq. (2.5d). We feel that removing the transportation components provides a better measure of relative prices.

Our figure for average automobile fleet efficiency (M) is based on the estimate in Table V of *Highway Statistics*. It was adjusted to

29 The national Consumer Price Index was adjusted using the following formula

\[
\text{ACPI} = \frac{\text{CPI} - w(TC)}{1 - w}
\]

where ACPI = adjusted Consumer Price Index  
CPI = Consumer Price Index  
w = weight of the transportation component in the Consumer Price Index  
TC = transportation component of the Consumer Price Index.

eliminate the effect of motorcycles by using the assumptions stated above. Our estimates of new car fuel efficiency (MN) are derived from the same data series. To estimate new car fuel efficiency, we had to assume that year-to-year changes in average automobile fleet efficiency were entirely due to changes in new car fuel efficiency; note that this assumption implies that the average fuel efficiency of autos scrapped in a given year is equal to the average auto fleet efficiency the previous year. We also assumed that new cars are driven 14,500 miles a year and used cars 9,500 miles. The same assumption is made by the Federal Highway Administration when estimating automobile operating costs.

**Empirical results.** Our results are given in Tables 3 to 8. Tables 3 and 4 contain estimates of Eqs. (2.17) and (2.18) in forms A and B, respectively. They are normalized on total population, adult population, and households. Tables 5 and 6 give estimates of Eq. (2.16)—the miles per gallon equation—in forms A and B. Tables 7 and 8 present estimates of Eq. (2.14) derived from our estimates of Eqs. (2.16), (2.17) and (2.18).

When we use form A, most of our estimates of the total elasticities of gasoline use and automobile travel with respect to gas price are between -0.37 and -0.45. They are higher than most other recent estimates, including our own estimates with pooled state time-series data. With form B, our estimates of the total elasticities decline when we normalize with total population and total households; they are now around -0.3. 30 When we normalize with driving age population, however, our estimates of elasticities are roughly the same for both forms A and B. The important point is that even our lowest estimates are higher than most other recent estimates, including our own estimate with pooled state time-series data. Most other studies have used broader measures

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30 Form B equations were estimates with the gasoline price wage rate variable expressed as \( \ln(p_r/W) \). However, the price of gasoline and the wage rate can be written as separate variables since \( \ln(p_r) = b \ln(W) \) where \( b \) is the estimated coefficient. In our tables, we write them as separate variables.
of highway fuel use; they have included fuel used by trucks and buses. Here our estimates are for gasoline used and miles traveled in automobiles. Thus, our results suggest that the elasticity of highway fuel use with respect to its price may be slightly higher than the overall elasticity of highway fuel use with respect to its price.\footnote{We performed a t-test of the null hypothesis that the elasticity of auto gasoline use equals the elasticity of total vehicle gasoline use, using the regression results from Eq. (2)(Table 2) and Eq. (4)(Table 3). The calculated t-statistic is 1.30, which is sufficient, using a one-tailed test, to reject the null hypothesis at the 90 percent level of confidence. This result also holds using Eq. (4)(Table 4). However, when equations normalized by total population of households are compared with the state data equation, the difference between elasticities of total vehicle and automobile fuel use is not significant at the 90 percent level.}

Our estimates of the elasticities of gasoline use and automobile travel with respect to automobile ownership are between 0.83 and 1.00 when form A is used; most are between 0.87 and 0.97. When we use form B, our estimates of these elasticities fall. They are between 0.58 and 0.85; most are between 0.63 and 0.73. Omitting the wage rate variable in form A might be biasing our estimates of the automobile ownership elasticities upward. Nevertheless, all the estimates indicate that as automobile ownership increases, average gasoline use and miles traveled per automobile fall slightly.

The dummy variable is a crude way to account for the effect of federal emission and safety standards; it is always significant at the 5 percent level or below. When the dummy variable is in the equation, it improves the equation's explanatory power. These results are consistent with the claim that federal emission and safety standards have lowered automobile miles per gallon and increased gasoline use.

We normalized our variables on driving age population as well as total population and total households. Most driving is done by people between 18 and 65 years of age. During the estimating period (1956 to 1973) this group first declined and then increased as a proportion of total population; the low point was 1963. When we looked at our data, we saw that the rate of growth of total automobile gasoline use increased around that time. These facts suggest that studies that normalize on
Table 3

ESTIMATED SHORT-RUN FUEL DEMAND FUNCTIONS: FORM A

<table>
<thead>
<tr>
<th>Eq. No.</th>
<th>Dependent Variable</th>
<th>Intercept</th>
<th>L(Pf)</th>
<th>L(A/P)</th>
<th>D</th>
<th>D.F.</th>
<th>S.E.</th>
<th>$R^2$</th>
<th>F</th>
<th>D-W</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>L(F/POP)</td>
<td>6.489</td>
<td>-0.384</td>
<td>0.994</td>
<td>0.047</td>
<td>13</td>
<td>0.0155</td>
<td>0.991</td>
<td>602.1</td>
<td>1.13</td>
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<td>(73.14)</td>
<td>(-2.42)</td>
<td>(11.80)</td>
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<td>L(V/POP)</td>
<td>9.032</td>
<td>-0.377</td>
<td>0.887</td>
<td>0.027</td>
<td>13</td>
<td>0.0117</td>
<td>0.993</td>
<td>792.5</td>
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<td>L(F/DPOP)</td>
<td>6.476</td>
<td>0.430</td>
<td>0.963</td>
<td>0.047</td>
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<td>0.0112</td>
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<td>5</td>
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<td>6</td>
<td>L(V/H)</td>
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NOTE: t-statistics in parentheses. Using a two-tailed test with 13 degrees of freedom, the t-statistics required to reject the null hypothesis that a coefficient equals zero are 2.16 (5 percent significance level) and 3.01 (1 percent significance level).
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<th>Eq. No.</th>
<th>Dependent Variable</th>
<th>Intercept</th>
<th>L(P_f)</th>
<th>L(W)^α</th>
<th>L(A/P)</th>
<th>D</th>
<th>D.F.</th>
<th>S.E.</th>
<th>R^2</th>
<th>F</th>
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<td>0.261</td>
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<td>0.305</td>
<td>0.688</td>
<td>0.036</td>
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<td>(4.31)</td>
<td>(2.96)</td>
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</tr>
<tr>
<td>3</td>
<td>L(F/DPOP)</td>
<td>6.013</td>
<td>-0.423</td>
<td>0.423</td>
<td>0.656</td>
<td>0.047</td>
<td>13</td>
<td>0.0155</td>
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<td>L(V/DPOP)</td>
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<td>0.398</td>
<td>0.583</td>
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<td>(4.65)</td>
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<td>L(F/H)</td>
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<td>0.731</td>
<td>0.051</td>
<td>13</td>
<td>0.0162</td>
<td>0.986</td>
<td>326.6</td>
<td>1.15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(96.77)</td>
<td>(-2.48)</td>
<td>(4.06)</td>
<td>(3.32)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>L(V/H)</td>
<td>8.999</td>
<td>-0.305</td>
<td>0.305</td>
<td>0.627</td>
<td>0.028</td>
<td>13</td>
<td>0.0117</td>
<td>0.990</td>
<td>513.9</td>
<td>1.21</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(192.08)</td>
<td>(-3.30)</td>
<td>(4.85)</td>
<td>(2.51)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

**NOTE:** t-statistics in parentheses.

^αCoefficient of L(W) constrained to equal the coefficient of L(P_f).
total population might be leaving out an important consideration. To see if this consideration made much difference, we estimated the same equations both on a per capita basis and on a per driving age adult basis; see Tables 3 and 4. We found that when we used driving age adults, the estimates of the elasticity of gasoline use with respect to automobile ownership increased. This increase is most striking in form B equations. These results suggest that failure to consider changes in the age composition of the population might have led to low estimates of the price elasticity of gasoline use in studies that covered time periods similar to ours and that normalized on total population.

MILES PER GALLON EQUATION

In this short-run analysis, the miles per gallon elasticity measures how much families would change their driving habits in response to a change in gasoline prices. Our estimates of that elasticity appear in Tables 5 and 6. With form A, our estimates fall between 0.15 and 0.25. They are significantly lower with form B, falling between 0.08 and 0.09. We are more confident in our estimates with the second form for two reasons. First, the omission of the wage rate variable in form A might be biasing the coefficient of gasoline price upward. Second, our estimate using form B is in closer agreement with our estimate using pooled state time-series data. In short, changes in gasoline prices will result in changes in auto gasoline use through altered driving habits, but this effect will probably be small.\footnote{The change in average highway and street speeds between 1973 and 1974 is consistent with the idea that higher gasoline prices induce people to change their driving habits. Gasoline prices rose sharply in late 1973 and early 1974. Average auto speeds dropped 6.4 miles per hour between 1973 and 1974.}

One might argue that the drop was due to (1) the 55 mph speed limit or (2) the recession of 1974-75 instead of higher gasoline prices. If the drop was due to the 55 mph speed limit, one would expect average speed to have dropped only on highways where many vehicles had been traveling faster than 55. In fact, average speeds also dropped on rural and suburban roads. Another factor besides the lower speed limit must have been at work.

The other reason might be the recession of 1974-75. We have found a strong statistical relationship between average automobile miles per
Table 5

ESTIMATED MILES PER GALLON ELASTICITY: FORM A

<table>
<thead>
<tr>
<th>Eq. No.</th>
<th>Dependent Variable</th>
<th>Intercept</th>
<th>L(Pf)</th>
<th>L(Z)</th>
<th>D</th>
<th>D.F.</th>
<th>S.E.</th>
<th>$R^2$</th>
<th>F</th>
<th>D-W</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>L(M)</td>
<td>2.656</td>
<td>0.298</td>
<td></td>
<td></td>
<td></td>
<td>15</td>
<td>0.0090</td>
<td>0.835</td>
<td>82.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(970.10)</td>
<td>(9.071)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>L(M)</td>
<td>2.605</td>
<td>0.294</td>
<td>0.032</td>
<td></td>
<td></td>
<td>14</td>
<td>0.0059</td>
<td>0.930</td>
<td>107.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(230.90)</td>
<td>(13.73)</td>
<td>(4.61)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>L(M)</td>
<td>2.656</td>
<td>0.170</td>
<td>-0.022</td>
<td></td>
<td></td>
<td>14</td>
<td>0.0069</td>
<td>0.901</td>
<td>73.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1248.74)</td>
<td>(3.67)</td>
<td>(3.30)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>L(M)</td>
<td>2.616</td>
<td>0.21</td>
<td>0.025</td>
<td></td>
<td></td>
<td>13</td>
<td>0.0049</td>
<td>0.950</td>
<td>163.0</td>
</tr>
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<td></td>
<td></td>
<td>(249.96)</td>
<td>(6.20)</td>
<td>(3.87)</td>
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<tr>
<td>5</td>
<td>L(MN)</td>
<td>2.475</td>
<td>0.346</td>
<td>0.103</td>
<td></td>
<td></td>
<td>14</td>
<td>0.0299</td>
<td>0.517</td>
<td>9.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(3.175)</td>
<td>(3.1)</td>
<td>(2.89)</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

NOTE: t-statistics in parentheses.
### Table 6

**Estimated Miles per Gallon Elasticity: Form B**

<table>
<thead>
<tr>
<th>Eq. No.</th>
<th>Dependent Variable</th>
<th>Intercept</th>
<th>L(Pf)</th>
<th>L(W)</th>
<th>L(Z)</th>
<th>L(Mt-1)</th>
<th>D</th>
<th>D.F.</th>
<th>S.E.</th>
<th>$R^2$</th>
<th>F</th>
<th>D-W</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>L(M)</td>
<td>2.720</td>
<td>0.088</td>
<td>-0.088</td>
<td>--</td>
<td>--</td>
<td>-0.020</td>
<td>14</td>
<td>0.0056</td>
<td>0.936</td>
<td>118.4</td>
<td>1.31</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(218.84)</td>
<td>(5.367)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(3.885)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>L(M)</td>
<td>2.701</td>
<td>0.088</td>
<td>-0.088</td>
<td>0.012</td>
<td>--</td>
<td>-0.019</td>
<td>13</td>
<td>0.0051</td>
<td>0.945</td>
<td>93.3</td>
<td>1.62</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(175.31)</td>
<td>(5.816)</td>
<td>(1.829)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(3.845)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>L(M)</td>
<td>1.153</td>
<td>0.036</td>
<td>-0.036</td>
<td>0.012</td>
<td>0.568</td>
<td>-0.010</td>
<td>12</td>
<td>-0.0040</td>
<td>0.967</td>
<td>119.2</td>
<td>2.65</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(2.318)</td>
<td>(1.772)</td>
<td>(2.468)</td>
<td>(3.114)</td>
<td></td>
<td></td>
<td></td>
<td>(1.995)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long Run</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5a</td>
<td>L(M)</td>
<td>2.669</td>
<td>0.083</td>
<td>-0.083</td>
<td>0.028</td>
<td>--</td>
<td>-0.024</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
that adding the unemployment rate as an independent variable improved the equations. Within our framework of analysis, the unemployment rate makes sense if it reflects the value Americans place on their time.

The inclusion of the dummy variable for 1968-72 also improved the equations' fit; the size of the dummy coefficient indicates that omission and safety standards have reduced average miles per gallon by about 15 percent between 1968 and 1972.\textsuperscript{33} This result must be treated with great caution, however, since the dummy variable is a very crude measure.

Our results concerning changes in driving habits strictly apply to only the first year after a change in gasoline prices. However, we can use the approach to explore questions important to a longer time frame. In such a time frame, Americans can get better miles per gallon not only by changing their driving habits but also by replacing their present automobiles with more efficient ones. If Americans adjusted to higher gasoline prices by buying more fuel efficient new cars, they might compensate for most of the increase in gasoline prices in about ten years. We tried in two ways to test the idea that they would make that adjustment.

First, we assumed that year-to-year changes in average auto fuel efficiency have been entirely due to changes in new car fuel efficiency. This assumption is just the opposite to the interpretation we have given our results. It allowed us to infer a time-series on new car fuel efficiency from our time-series on average automobile miles per gallon; see our discussion of data sources above. We regressed our estimates

\begin{quote}
\textsuperscript{33} James Sweeney has also found a similar, small effect for emission and safety standards during the period. See Sweeney, op. cit., p. 17.
\end{quote}
of new car fuel efficiency against gasoline price and the unemployment rate; see Eq. (5) in Table 5. This equation indicates that the percentage increase in new car fuel efficiency would be about one-third the percentage increase in real gasoline prices. We estimated the average fuel efficiency of new cars to be 12.7 miles per gallon in 1972; thus, a one-third increase would bring new car fuel efficiency to about 17 miles per gallon.

Second, we introduced average automobile miles per gallon lagged one year as an independent variable in form B of our equation; see Eq. (5) in Table 6. This allows us to compute a long-run elasticity of average automobile miles per gallon with respect to gasoline price; see Eq. (5a). In the long run, Americans could not only adjust their driving habits but also change to more fuel efficient automobiles. The long-run elasticity is low; it is close to the short-run elasticity. In fact, Eq. (5a) would imply that we might be overestimating the short-run change in average auto miles per gallon.

Our tests are consistent with two notions about how Americans would adjust to higher real gasoline prices in the long run. First, Americans would respond by purchasing more fuel efficient new cars. Second, for likely increases in the real price of gasoline, the increases in new car fuel efficiency would not be extremely large.

**DERIVED EQUATIONS**

Finally, to aid comparison, we converted all the estimated equations to the same form—Eq. (2.14). We used the equations in Table 3 and Eq. (3) in Table 5 for form A; we used the equations in Table 4 and Eq. (4) in Table 6 for form B. The results are given in Tables 7 and 8. The derived equations correspond to the estimated equations with the same numbers in Tables 3 and 4. The odd-numbered equations in the tables come from estimated equations that had automobile gasoline use as the dependent variable. The even-numbered ones come from estimated equations that had automobile miles traveled as the dependent variable.

The results in Tables 7 and 8 display several points. First, it seems to make a difference whether the dependent variable in the basic equation is gasoline use or vehicle miles. When it is gasoline use, the
gasoline price elasticity is lower (in absolute value) and the miles per gallon elasticity is higher in equations that are otherwise alike. The difference is greatest with form A, but it persists in form B. Thus, equations derived from ones with gasoline use as the dependent variable would make policies that increase gasoline prices look less effective; they would make policies that increase average automobile miles per gallon look more effective.

Second, a 10 percent increase in average automobile miles per gallon would result in a less than 10 percent saving in automobile gasoline use. An increase in average automobile miles per gallon reduces the cost of gasoline per mile; lower costs per mile lead to more miles traveled.

Normalizing with driving age population, rather than total population, makes a difference. (Compare Eqs. (1) and (3) and Eqs. (2) and (4) in Table 8.) In past studies, failure to account for changes in the age composition of the population might have led to low estimates of the gasoline price elasticity.

Finally, when we use similar equations, we get similar results with state and national data. Equation (1) in Table 8 is most similar to the equations we estimated with state time-series data (Eq. (5), Table 2). Both equations have fuel use per capita as their dependent variable. The equations differ in that the former Eq. (1) has average wage rates rather than personal disposable income per capita as an independent variable. Their elasticities of fuel use with respect to gasoline price, income (or the wage rate), average miles per gallon, and vehicle (or automobile) ownership are very close.
Table 7
DERIVED SHORT-RUN FUEL DEMAND FUNCTIONS: FORM A

<table>
<thead>
<tr>
<th>Eq. No.</th>
<th>Dependent Variable</th>
<th>Intercept</th>
<th>LP&lt;sub&gt;ε&lt;/sub&gt;</th>
<th>L(M)</th>
<th>L(A/P)</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>L(F/POP)</td>
<td>8.461</td>
<td>-0.258</td>
<td>-0.742</td>
<td>0.994</td>
<td>0.031</td>
</tr>
<tr>
<td>2</td>
<td>L(F/POP)</td>
<td>7.819</td>
<td>-0.455</td>
<td>-0.545</td>
<td>0.867</td>
<td>0.038</td>
</tr>
<tr>
<td>3</td>
<td>L(F/DPOP)</td>
<td>8.301</td>
<td>-0.313</td>
<td>-0.687</td>
<td>0.963</td>
<td>0.032</td>
</tr>
<tr>
<td>4</td>
<td>L(F/DPOP)</td>
<td>7.834</td>
<td>-0.472</td>
<td>-0.528</td>
<td>0.877</td>
<td>0.035</td>
</tr>
<tr>
<td>5</td>
<td>L(F/H)</td>
<td>8.388</td>
<td>-0.289</td>
<td>-0.711</td>
<td>0.970</td>
<td>0.032</td>
</tr>
<tr>
<td>6</td>
<td>L(F/H)</td>
<td>7.996</td>
<td>-0.444</td>
<td>-0.556</td>
<td>0.864</td>
<td>0.035</td>
</tr>
</tbody>
</table>

Odd-numbered equations are derived results from estimating equations with auto fuel use as dependent variable. Even-numbered equations are derived results from estimating equations with auto miles traveled as dependent variable.

Table 8
DERIVED SHORT-RUN FUEL DEMAND FUNCTIONS: FORM B

<table>
<thead>
<tr>
<th>Eq. No.</th>
<th>Dependent Variable</th>
<th>Intercept</th>
<th>L(P&lt;sub&gt;ε&lt;/sub&gt;)</th>
<th>L(M)</th>
<th>L(W)</th>
<th>L(Z)</th>
<th>L(A/P)</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(F/POP)</td>
<td>8.337</td>
<td>-0.190</td>
<td>-0.810</td>
<td>0.190</td>
<td>0.010</td>
<td>0.849</td>
<td>0.42</td>
</tr>
<tr>
<td>2</td>
<td>(F/POP)</td>
<td>7.703</td>
<td>-0.334</td>
<td>-0.666</td>
<td>0.334</td>
<td>-0.004</td>
<td>0.688</td>
<td>0.42</td>
</tr>
<tr>
<td>3</td>
<td>(F/DPOP)</td>
<td>7.723</td>
<td>-0.367</td>
<td>-0.633</td>
<td>0.367</td>
<td>0.008</td>
<td>0.656</td>
<td>0.35</td>
</tr>
<tr>
<td>4</td>
<td>(F/DPOP)</td>
<td>7.658</td>
<td>-0.431</td>
<td>-0.569</td>
<td>0.431</td>
<td>-0.004</td>
<td>0.583</td>
<td>0.30</td>
</tr>
<tr>
<td>5</td>
<td>(F/H)</td>
<td>8.328</td>
<td>-0.254</td>
<td>-0.746</td>
<td>0.254</td>
<td>0.009</td>
<td>0.731</td>
<td>0.37</td>
</tr>
<tr>
<td>6</td>
<td>(F/H)</td>
<td>8.097</td>
<td>-0.334</td>
<td>-0.666</td>
<td>0.334</td>
<td>-0.004</td>
<td>0.627</td>
<td>0.35</td>
</tr>
</tbody>
</table>

α: See footnote α in Table 7.
III. LONG-RUN FUEL DEMAND WITH AUTOMOBILE STOCK ADJUSTMENT

Section II dealt with short-run changes in gasoline use. The short run was defined as the period before vehicle ownership changes. Short-run changes in gasoline use are due to changes in vehicle miles traveled or in driving habits.

Here we consider changes in the number of automobiles owned. Our interest is in how changes in real gasoline prices and new car prices affect automobile ownership. Studying how ownership changes allows us to consider long-run adjustments in gasoline use.

We are interested in more than changes in total ownership, however; we are also concerned about how total ownership changes would come about; changes in the number of automobiles owned can come about through changes in either new car sales or automobiles scrapped.

We consider changes in only the total number of automobiles owned. Unfortunately, with the data available, we cannot consider how the ownership of automobiles of different weights or horsepower changes. This means that our estimates probably understate the long-run effects of higher real gasoline prices on gasoline use, because we are not including the effect of a shift to more efficient cars.

RELATED RESEARCH

Scope

Most research deals solely with new car sales or automobiles scrapped. It does not consider what determines total automobile ownership; in fact, many studies take total automobile ownership as an independent variable. Since our main interest is in how total automobile ownership would adjust, we will not discuss research that deals solely with new car sales or automobiles scrapped.

We are concerned about the effect of changes in real gasoline prices on gasoline use through changes in automobile ownership. Until recently, researchers have not considered gasoline prices as a factor influencing
auto ownership, new car sales, or automobiles scrapped. Research that does not include gasoline prices is not really germane and is not included here.

Summary Description

We describe three recent research efforts performed by Chase Econometric Associates, the Transportation Systems Center (TSC), and the Federal Energy Administration (FEA). Each is an analytic model with some econometric relationships. Each model attempts to include the entire adjustment process; they have relationships for automobile (or private vehicle) miles traveled as well as for adjustment in the automobile stock. The former were discussed above; here we focus on the automobile ownership adjustment mechanisms.

The analytic models developed by Chase and TSC use similar general structures; the components of each model are related in similar ways. They differ in the details of each component, the data used to estimate behavioral relationships, and the techniques used to estimate them. Both proceed in the following manner. First, total new car unit sales are forecast as a function of new car price, gasoline price, and other independent variables. Total new car sales are then split between size classes with a set of market share equations; generally, they are functions of new car prices, gasoline price, and other economic and demographic variables. The market share equations are used to estimate new car sales by size class, e.g., standard, intermediate. These estimates are used to calculate average new car fuel efficiency. The estimates of new car sales by size class are also added to last year's automobile ownership. Next, this year's automobile ownership is calculated by applying fixed scrappage rates to total automobile ownership last year. Finally, automobile miles traveled are forecast as a function of this year's automobile ownership, gasoline price, and other variables.

1 See Chase Econometric Associates, op. cit. The work done at the Transportation Systems Center is contained in several documents. Some of the implications of the model are discussed in U.S. Department of Transportation and U.S. Environmental Protection Agency, Potential for Motor Vehicle Fuel Economy Improvement, Washington, D.C., October 1974. More details are given in Robert Schuessler and Rene Smith's "Working
The FEA model has a different structure and line of causation. It runs from the gasoline price per mile through automobile miles traveled, and new car sales to automobile ownership. First, the FEA model forecasts the average fuel efficiency of new cars actually bought, i.e., allowing the average weight of new cars to change; it is a function of last year's gasoline price and (by assumption) the technical fuel efficiency of new cars, i.e., holding new car weight constant.\footnote{The estimated equation is}

\[
L(MN) = a_0 + a_1 L(P_f^{t-1})
\]

where MN = average new car fuel efficiency
\[P_f^{t-1}\] = last year's gasoline price
\[a_0, a_1\] = estimated parameters.

This econometric relationship plays the same role in the FEA model that the market share equations play in the Chase and TSC models. The estimate of average new car fuel efficiency is used to calculate the average fuel efficiency for the entire fleet and the average price of gasoline per mile. The gasoline price per mile, along with standard macroeconomic variables, is used to forecast automobile miles traveled. This equation was discussed in a previous section. Next, the forecast of automobile miles traveled is used, along with adjusted automobile ownership and standard macroeconomic variables, to forecast total new

car sales. Finally, automobile ownership is calculated by adding total new car sales to last year's automobile ownership after it has been reduced by a fixed scrappage rate.

The structures of the models can be contrasted. In the Chase and TSC models, total automobile ownership is forecast first. Then, this forecast is used to predict vehicle miles traveled. The causation runs the other way in the FEA model. The number of automobile miles traveled is forecast first; it is then used to predict new car sales.

We noted that the models differ in how they forecast new car fuel efficiency. Chase and TSC use a set of market share equations. This gives their models the potential to deal with new car excise taxes that are graduated by weight or horsepower. In the FEA model, average new car fuel efficiency is a simple function of last year's real gasoline price. Consequently, the model cannot handle policies that act through changes in relative new car price. (In fact, new car prices appear to have no impact on the number sold in the FEA model.)

Another difference is how the price of gasoline is measured. Chase uses the price of gasoline per gallon. The TSC and FEA models use the price of gasoline per mile—gasoline price divided by average auto fuel efficiency. They assert that rational people would base their decisions on the price of gasoline per mile—not per gallon. For since real gasoline prices help determine average auto fuel efficiency in their models, the effect of higher real gasoline prices on new car sales is partially offset by improved automobile fuel efficiency in the models.

In all three analyses, an autonomous increase in new car fuel efficiency would shift new car purchases toward larger cars. This shift

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3 The assertion is probably right, but it must be handled with care. If applied too broadly, it can lead to faulty policy conclusions. For example, using the real price of gasoline per mile as a determinant of new car sales implies that increasing new car fuel efficiency would increase new car sales. If the price and other desired characteristics of new cars did not change, this implication is reasonable. (All of the models assume that other characteristics of new cars do not change.) However, it does not follow, as some have suggested, that a government policy that both increased new car fuel efficiency and changed other characteristics of new cars would result in increased sales. All econometric work to date has assumed that the performance and comfort of cars are constant. Consequently, we cannot weigh what would happen if these characteristics changed.
would reduce the effectiveness of autonomous increase in new car fuel efficiency for saving gasoline. The Chase model attempts to estimate the shift empirically; however, it does not provide consistent estimates for all weight classes. The TSC and FEA studies incorporate the shift into their analyses by assumption.

A major reason for building each model was to study several alternative policies in the same context. We show the types of policies that can be handled by each model in Table 9. Although each model can handle several types, none can handle all of them.

Table 10 compares the first-year elasticities of total new car sales with respect to real gasoline and new car prices. Where applicable, the t-statistics associated with the elasticities are in parentheses below the elasticities. Note that when real gasoline prices are expressed per mile, the elasticities are lower.

Evaluation

What matters is whether the models give the right policy guidance. In all the models, the only adjustment in the automobile stock that responds to policy decisions is new car sales; the percentage of automobiles scrapped is a fixed percentage of the total stock. This feature might mask important impacts of some policies. For example, a graduated tax on new cars is likely to shift the demand curves for different types of used cars. The demand for inefficient used cars would increase and they would be operated longer. Since these models ignore changes in auto scrappage rates, they would not predict such an adverse result.

Second, the reactions of automobile makers to policy actions are not considered; the models trace out only new car buyers' reactions. How automobile makers react might be especially important in predicting how taxes graduated by new car size or efficiency would work. The purpose of such a policy is to shift the mix of new car sales toward more efficient models by increasing the after-tax price of less efficient cars relative to the after-tax price of more efficient
Table 9
POLICY ANALYSIS CAPACITY OF CHASE, TSC, AND FEA MODELS

<table>
<thead>
<tr>
<th>Factor Included</th>
<th>Chase</th>
<th>TSC</th>
<th>FEA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline price</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Relative new car price</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>New car fuel efficiency</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Average speed</td>
<td></td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

Table 10
TOTAL NEW CAR SALES ELASTICITIES
First Year After Price Change

<table>
<thead>
<tr>
<th>Elasticity With Respect to:</th>
<th>Model</th>
<th>Gasoline Price</th>
<th>New Car Price</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Chase</td>
<td>-0.82</td>
<td>-0.88</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(-2.3)</td>
<td>(-2.7)</td>
</tr>
<tr>
<td></td>
<td>TSC</td>
<td>-0.20</td>
<td>-0.60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(-0.6)</td>
<td>(-1.7)</td>
</tr>
<tr>
<td></td>
<td>FEA</td>
<td>-0.27</td>
<td>N.A.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(N.A.)</td>
<td></td>
</tr>
</tbody>
</table>

NOTE: t-statistics in parentheses.

\(^a\) Degrees of freedom of equation not published.

\(^b\) Gasoline price per mile.

\(^c\) Derived value.
ones. Automobile makers, however, with fixed investment in facilities, might react by lowering the pretax price of less efficient cars relative to the pretax price of more efficient new cars. If they did, the models would overestimate the effectiveness of graduated taxes.

**ANALYSIS**

In this section, we are concerned about how changes in real gasoline and car prices would affect total automobile ownership. We are also concerned with how that total would adjust to changes through the number of autos sold and scrapped.

**Assumptions**

In our analysis, the real prices of gasoline and new cars are taken as given. We assume that any quantity of gasoline or new cars can be purchased at prices determined outside the analysis. Therefore, the model cannot be used to forecast market clearing price-quantity combinations. Rather, our purpose is to study how households would adjust their demand for automobile services as a result of changes in the real prices of gasoline and new cars.

Total automobile ownership equals new cars plus used cars. We assume that new and used cars have the same average fuel efficiency; otherwise, the model would be very complex. For good reasons, however, we still treat new and used cars as different commodities. From the viewpoint of buyers, new cars might involve lower information and transaction costs than used cars.\(^4\)

Another important consideration is that the supply conditions for new and used cars are different. New cars are supplied by a production process; used cars are supplied from last year's automobile ownership. At any time, there is a maximum limit to the number of used cars that can be supplied; used cars supplied this year cannot exceed total auto-

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mobile ownership last year. Above some level of used car prices, the supply of used cars becomes totally inelastic; below that level, the difference between last year's total automobile ownership and this year's used car ownership consists of automobiles scrapped. Thus, the demand for used cars implies the number of autos scrapped.

New and Used Car Markets

Figure 1 summarizes our assumptions about and description of the new and used car markets. The demand curves for new and used cars are \( D_n \) and \( D'_u \), respectively. We are assuming a perfectly elastic supply of new cars at price \( P_n \); it is represented by curve \( S_n \). The number of new cars sold is \( N \). The supply curve of used cars is \( S'_u \); it becomes perfectly inelastic at last year's automobile ownership \( (A_{t-1}) \). Used car demand equals used cars supplied at price level \( P_u \) and quantity \( U \).

There is another commodity in our analysis—gasoline. Families use gasoline along with new cars to "produce" automobile miles traveled; in the jargon of economics, we assume gasoline to be a gross complement to both new cars and used cars. An increase in the price of gasoline \( (P_f) \) would increase the cost of producing automobile miles traveled and families would produce fewer of them. Fewer miles traveled would mean not only less use of gasoline, but also less demand for both new and used cars. Thus, an increase in gasoline price would cause the demand curves for both new and used cars to shift to the left in Fig. 1.

We assume that the demands for new cars and used cars are functions of average new car prices \( (P_n) \), average used car prices \( (P_u) \), average gasoline prices \( (P_f) \), and average incomes \( (Y) \). The demand functions can be stated as follows:

---

5 The reader might object to this statement for two reasons. First, used cars could be imported. In the past, however, imports have not been an important source of supply to the American market. We believe that legal standards for automobiles in this country will prevent used car imports from being important in the future.

Second, every year some cars are damaged beyond repair at any cost.
Demand for new car services:  \( N = N(P_n, P_u', P_f', Y) \)  \( (3.1) \)

Demand for used car services:  \( U = U(P_n, P_u', P_f', Y) \)  \( (3.2) \)

The quantities of new and used cars demanded are negatively related to their own prices and positively related to each other's prices. Both are negatively related to average gasoline price and positively related to average incomes.

To get a solution for the used car market, we need a supply relationship for used cars. As mentioned above, used car supply conditions are unusual. Used cars are "supplied" from last year's automobile ownership, not produced; consequently, the used car supply relationship takes a different form. We postulate an "inverse" supply function, i.e., price is a function of quantity supplied. It is the following:

\[
\text{Used car price: } P_u = P_u(A_{t-1}, P_n, P_f, Y) \tag{3.3}
\]

Equation (3.3) says that average used car prices are a function of the maximum available supply of used cars (automobile ownership last year--\( A_{t-1} \)), new car prices, average gasoline prices, and average incomes. Average used car price and automobile ownership last year are negatively related; the more used cars available, the lower their average price. Average gasoline price is also negatively related to average used car prices. Average new car prices and average incomes are positively related to average used car prices.

Consequently, the available supply of used cars is really less than last year's total automobile ownership. However, since we had no way to know what proportion of scrapped cars could not have been kept going at any cost, we ignored the factor.

6. The conclusion that higher gasoline prices lead to reduced demand for both new and used cars stems directly from our assumption that gasoline is a gross complement to both new and used cars. This assumption is implicit in our short-run model of Sec. II, since we do not distinguish between new and used cars by fuel efficiency characteristics. In a more complete model--one that differentiated the automobile stock
Gasoline Price Change

Figure 2 portrays the effects of a gasoline price increase on the new and used car markets. Such an increase causes the used car demand curve to shift to the left, from $D_u^u$ to $D_u^u'$. It also leads to an increased supply (or a decreased supply price) of used cars; the shift is from $S_u^u$ to $S_u^u'$. As a result, the average price of used cars falls from $P_u$ to $P_u^1$.

In the new car market, the demand curves shift to the left for two reasons. First, the increase in gasoline price acts directly to reduce new car demand. Second, since new cars and used cars are gross substitutes, the fall in used car prices acts to further reduce new car sales. For both reasons, new car sales fall from $N$ to $N^1$ in Fig. 2.

New Car Price Change

Figure 3 depicts the effects of an increase in new car prices on the new and used car markets. The increase in average new car prices is represented by the upward shift in the new car supply curve; the new supply curve is $S_n^2$, with average new car prices $P_n^2$. With higher new car prices, families would demand more used cars. (In this context, an increased demand for used cars might only mean that more families are holding onto their present cars longer.) The used car demand curve shifts to the right; average used car prices increase to $P_u^2$ and automobiles scrapped decline to $(A_{t-1} - U^2)$. However, higher used car prices result in some Americans returning to the new car market; the new car demand curve shifts to the right.

When the markets are fully adjusted, new car sales are $N^2$. Note that when price rises in the used car market are included, the fall by age--higher fuel prices would induce changes in the prices of new and used cars according to their relative fuel efficiencies. The above conclusion might then be invalid; for example, if used cars had greater fuel efficiency than new cars, higher fuel prices could induce an increased demand for used cars.
Fig. 1 — New and used car markets

Fig. 2 — Effect of gasoline price increase on new and used car markets
Fig. 3—Effect of increased new car prices on new and used car markets

in new car sales is less than the initial fall due to new car prices alone.7

EMPIRICAL RESULTS

Data Series and Model Changes

Our analytic framework is not entirely specific. Available data can take several forms and still be consistent with the analytic structure. Neither does the model account for all sources of variation in car ownership and new car sales. To account for other sources of variation, we added several independent variables.

We had to choose a basis for normalizing the model. We chose to use two bases: driving age population (DPOP) and total population (POP).

7We are assuming that the new car market is Hicksian perfectly stable. Otherwise, the increase in used car prices could cause the new car demand curve to shift so far to the right as to move \( N^2 \) to the right of \( N \).
We also had to decide whether to measure income by current income, permanent income, or expenditures. After some experimentation, we chose permanent income because it provided better regression results. In the remainder of this section, the symbol "y" refers to permanent income.

We changed the model by entering the permanent income variable in the new car sales equation in a nonstandard way. In the other equations, the income variable is entered as permanent income per household. In the new car sales equation, it is entered as the ratio between this year's and last year's permanent income per household, i.e.,

\[
\frac{Y_t/Y_{t-1}}{H_t/H_{t-1}}
\]

In this form, the income variable better reflects year-to-year growth in permanent income.\(^8\)

Gasoline price was dropped as an independent variable in the new

---

\(^8\)Note that this change does not prevent us from calculating an income elasticity of demand for new cars when the equations are estimated in linear form. The income elasticity of demand for new cars is defined as follows:

\[
\frac{\partial N}{\partial (Y_t/H_t)} \cdot \frac{Y_t H_t}{N}
\]

Now, \(\frac{\partial N}{\partial (Y_t/H_t)}\) can be written:

\[
\frac{\partial N}{\partial (Y_t/H_t)} = \frac{\partial}{\partial \left(\frac{Y_t}{Y_{t-1}}/\frac{H_t}{H_{t-1}}\right)} \cdot \frac{\partial \left(\frac{Y_t}{Y_{t-1}}/\frac{H_t}{H_{t-1}}\right)}{\partial (Y_t/H_t)}
\]

\[
\frac{\partial N}{\partial \left(\frac{Y_t}{Y_{t-1}}/\frac{H_t}{H_{t-1}}\right)} \cdot \frac{1}{\frac{Y_{t-1}}{H_{t-1}}}
\]

Thus,

\[
\frac{\partial N}{\partial (Y_t/H_t)} \cdot \frac{Y_t H_t}{N} = \frac{\partial}{\partial \left(\frac{Y_t}{Y_{t-1}}/\frac{H_t}{H_{t-1}}\right)} \cdot \frac{\partial \left(\frac{Y_t}{Y_{t-1}}/\frac{H_t}{H_{t-1}}\right)}{N}
\]
car demand equation. After trying many combinations of variables, we were unable to get a good relationship between new car sales and gasoline price when used car price was also in the equation. With gasoline price out of the equation, the entire influence of changes in gasoline prices on new car sales runs through used car prices; for example, higher gasoline prices would result in lower used car prices, and lower used car prices would lead to reduced new car sales.

In our above review of related research, we mentioned the discussion about whether the gasoline price variable should be defined in terms of price per gallon or per mile. With that discussion in mind, we estimated the model in both ways. Gasoline price now appears as an independent variable in the used car demand and used car price equations. Since gasoline price directly affects used car ownership and price, we defined gasoline price per mile as this year's gasoline price divided by last year's average fuel efficiency ($P_{gt}/M_{t-1}$).

Used car fuel efficiency might be a better measure than total automobile fuel efficiency. New car buyers can adjust for higher gasoline prices by purchasing more fuel efficient new cars. Used car owners have a more difficult time adjusting for higher gasoline prices. Used cars come from an existing stock of automobiles; its technical fuel efficiency is already fixed. Thus, the fuel efficiency of used cars can be changed only through different driving habits and different scrap-page rates for efficient and inefficient cars.

Data Sources

What we have called automobile ownership and new car sales are actually automobile registration and automobile domestic production plus net imports, respectively. These data series were given to us by the Federal Highway Administration. What we have referred to as used car fuel efficiency is actually average automobile fuel efficiency one year i.e., the elasticity of new car sales with respect to income equals the elasticity of new car sales with respect to the ratio of this year's income to last year's income. Note that the first part of the product on the right is the estimated coefficient.
earlier. Our estimates of this data series are also based on Federal Highway Administration data. How we estimated this data series was described in the last section.

For the new car price, used car price, and gasoline price variables, we used components of the Consumer Price Index with 1958 = 100. All the price variables were deflated by the national Consumer Price Index after its transportation component was removed.

Our final change was to add a dummy variable (ST) to account for major strikes in automobile manufacturing and related industries. It is set equal to -1 the year of the strike and +1 the following year; otherwise, it is zero. By using such a dummy variable, we are implicitly assuming that new car sales not made in a strike year are made the following year. In addition to strike years, the dummy variable was used for 1959; the strike in the steel industry that year had a major impact on new car production.

A real permanent disposable income data series for the years 1954 to 1969 was given to us by F. C. Wykoff. We updated it to 1972, using data on disposable personal income from Table C-18 of the 1973 Economic Report of the President.

Estimates of driving age population (people aged 18 to 64) and households came from the Bureau of the Census's Current Population Reports: Population Characteristics, Series P-20.

The model was estimated with annual observations for the years 1954 to 1972.

**Estimation Technique**

In the model with gasoline price per gallon as an independent variable, the new car demand and used car demand equations were estimated using both Ordinary Least Squares and Two Stage Least Squares.

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Both techniques were tried because, with a very small sample size, it was not clear which would give better results. Since only variables whose values are determined outside the model are independent variables in the used car price equation, it was estimated only with Ordinary Least Squares. In the model with gasoline price per mile as an independent variable, only the Two Stage Least Squares estimates of the new car demand and used car demand equations are presented.

Findings

Our results are presented in Tables 11 to 14. The estimated equations in Tables 11 and 12 have new car sales and used car ownership normalized with driving age population. The equations in Table 12 use logarithmic values of the variables. In each table, the first three equations are estimates of the new car demand equation. The second three are estimates of the used car demand equation, while the last two are estimates of the used car price equation. Tables 13 and 14 are similar to Tables 11 and 12; the only difference is that new cars, used car ownership, and total automobile ownership are normalized with total households.

Our choice of estimating technique makes a difference; it is most apparent in the used car demand equation. When Two Stage Least Squares (TSLS) is used instead of Ordinary Least Squares (OLS), the coefficients in the used car demand equation change greatly; note that all the price elasticities become larger. The bias is clear in the equations estimated with OLS, but they have much smaller standard errors. The choice between estimating techniques boils down to a trade-off between low standard errors and consistent estimates of the coefficients. Note also that when TSLS is used, the coefficients of used car price rise in the new car demand equations normalized on total households.

Let us take each equation in turn. In the new car demand equation, the own price elasticity, with used car price constant, is higher than the own price elasticities in the studies reviewed above. However, many other estimates of this elasticity have been made; our own is within the
### Table II

**AUTOMOBILE STOCK ADJUSTMENT PROCESS PER DRIVING AGE ADULT, LINEAR FORM**

<table>
<thead>
<tr>
<th>Eq. No.</th>
<th>Dependent Variable</th>
<th>Intercept</th>
<th>$P_{t}$</th>
<th>$P_{t}/M$</th>
<th>$P_{n}$</th>
<th>$P_{u}$</th>
<th>$Y/H$</th>
<th>$\Delta Y/H$</th>
<th>$A_{t-1}/DR$</th>
<th>ST</th>
<th>Estimation Technique</th>
<th>DF</th>
<th>$R^2$</th>
<th>SE</th>
<th>$F$</th>
<th>D-W</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>N/DPOP</td>
<td>-0.209</td>
<td>-0.122</td>
<td>0.055</td>
<td>0.325</td>
<td>0.009</td>
<td>(6.529)</td>
<td>(2.125)</td>
<td>(2.484)</td>
<td></td>
<td>OLS</td>
<td>14</td>
<td>0.73</td>
<td>0.00641</td>
<td>12.96</td>
<td>2.66</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(-1.659)</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>N/DPOP</td>
<td>-0.209</td>
<td>-0.122</td>
<td>0.061</td>
<td>0.324</td>
<td>0.009</td>
<td>(6.378)</td>
<td>(1.831)</td>
<td>(2.462)</td>
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<td>TSLS$^{2}$</td>
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<td>0.00641</td>
<td>34.69</td>
<td>2.66</td>
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<tr>
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</tr>
<tr>
<td>3</td>
<td>N/DPOP</td>
<td>-0.209</td>
<td>-0.123</td>
<td>0.063</td>
<td>0.322</td>
<td>0.009</td>
<td>(6.429)</td>
<td>(1.940)</td>
<td>(2.451)</td>
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<td>TSLS$^{2}$</td>
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<tr>
<td>4</td>
<td>U/DPOP</td>
<td>-0.164</td>
<td>0.476</td>
<td>-0.156</td>
<td>0.141</td>
<td>0.003</td>
<td>(3.322)</td>
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<td>OLS</td>
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<td>0.01029</td>
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<tr>
<td>5</td>
<td>U/DPOP</td>
<td>-0.474</td>
<td>0.919</td>
<td>-0.448</td>
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<td>0.011</td>
<td>(2.964)</td>
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<td>53.38</td>
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</tr>
<tr>
<td>6</td>
<td>U/DPOP</td>
<td>-0.359</td>
<td>-9.037</td>
<td>0.816</td>
<td>-0.407</td>
<td>0.189</td>
<td>(1.424)</td>
<td>(3.591)</td>
<td>(2.915)</td>
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<td>TSLS$^{2}$</td>
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<tr>
<td>7</td>
<td>$P_{u}$</td>
<td>-1.142</td>
<td>1.888</td>
<td>0.401</td>
<td>-1.863</td>
<td>-0.024</td>
<td>(5.706)</td>
<td>(3.692)</td>
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<td>OLS</td>
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</tr>
<tr>
<td>8</td>
<td>$P_{u}$</td>
<td>-0.987</td>
<td>-15.832</td>
<td>1.7887</td>
<td>0.37983</td>
<td>-1.6150</td>
<td>(-2.171)</td>
<td>(6.034)</td>
<td>(3.747)</td>
<td></td>
<td>OLS</td>
<td>13</td>
<td>0.72</td>
<td>0.03469</td>
<td>10.09</td>
<td>2.24</td>
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<td>(-2.171)</td>
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<td></td>
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</tr>
</tbody>
</table>

$a$ Instrumental variables: Gasoline price ($P_{t}$), new car price ($P_{t}$), permanent income per household ($Y/H$), change in permanent income per household ($\Delta Y/H$), last year's auto ownership per driving age adult ($A_{t-1}/DPOP$) or per household ($A_{t-1}/H$), and the strike dummy variable (ST).

$b$ Instrumental variables: Used car gasoline price per mile ($P_{t}/M_{t-1}$), permanent income per household ($Y/H$), change in permanent income per household ($\Delta Y/H$), last year's auto ownership per driving age adult ($A_{t-1}/DPOP$) or per household ($A_{t-1}/H$), and the strike dummy variable (ST).
Table 12
AUTOMOBILE STOCK ADJUSTMENT PROCESS PER DRIVING AGE ADULT, LOGARITHMIC FORM

<table>
<thead>
<tr>
<th>Eq. No.</th>
<th>Dependent Variable</th>
<th>Intercept</th>
<th>L(P_t)</th>
<th>L(P_t/M)</th>
<th>L(P_n)</th>
<th>L(Y/H)</th>
<th>L(AY/H)</th>
<th>L(A_{t-1}/DPOP) ST</th>
<th>Estimation Technique</th>
<th>D-S</th>
<th>R^2</th>
<th>S.E.</th>
<th>F</th>
<th>D.W.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>L(H/DPOP)</td>
<td>-2.931</td>
<td>-1.629</td>
<td>0.958</td>
<td>5.316</td>
<td>0.131</td>
<td></td>
<td>OLS</td>
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^aInstrumental variables: Gasoline price (P_e), new car price (P_n), permanent income per household (Y/H), change in permanent income per household (AY/H), last year's auto ownership per driving age adult (A_{t-1}/DPOP) or per household (A_{t-1}/H), and the strike dummy variable (ST).

^bInstrumental variables: Used car gasoline price per mile (P_{e}/M_{e-1}) permanent income per household (Y/H), change in permanent income per household (AY/H), last year's auto ownership per driving age adult (A_{t-1}/DPOP) or per household (A_{t-1}/H), and the strike dummy variable (ST).
### Table 13

AUTOMOBILE STOCK ADJUSTMENT EQUATIONS PER HOUSEHOLD, LINEAR FORM

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<tr>
<th>Eq. No.</th>
<th>Dependent Variable</th>
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<th>$P_{f/N}$</th>
<th>$P_u$</th>
<th>$Y/H$</th>
<th>$\Delta Y/H$</th>
<th>$A_{t-1/H}$</th>
<th>ST</th>
<th>Estimation Technique</th>
<th>DF</th>
<th>$R^2$</th>
<th>S.E.</th>
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\(^a\)Instrumental variables: Gasoline price ($P_f$), new car price ($P_u$), permanent income per household ($Y/H$), change in permanent income per household ($\Delta Y/H$), last year's auto ownership per driving age adult ($A_{t-1/DPOP}$) or per household ($A_{t-1/H}$), and the strike dummy variable (ST).

\(^b\)Instrumental variables: Used car gasoline price per mile ($P_{f/M_{t-1}}$), permanent income per household ($Y/H$), change in permanent income per household ($\Delta Y/H$), last year's auto ownership per driving age adult ($A_{t-1/DPOP}$) or per household ($A_{t-1/H}$), and the strike dummy variable (ST).
### Table 14

**AUTOMOBILE STOCK ADJUSTMENT EQUATIONS PER HOUSEHOLD, LOGARITHMIC FORM**

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<th>( L(Y/H) )</th>
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<td>(-2.164)</td>
<td>(5.675)</td>
<td>(3.291)</td>
<td>(-1.998)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\( ^a \) Instrumental variables: Gasoline price \( (P_f) \), new car price \( (P_u) \), permanent income per household \( (Y/H) \), change in permanent income per household \( (\Delta Y/H) \), last year's auto ownership per driving age adult \( (A_{t-1}/(DPOT)) \) or per household \( (A_{t-1}/H) \), and the strike dummy variable \( (ST) \).

\( ^b \) Instrumental variables: Used car gasoline price per mile \( (P_f/N_{t-1}) \), permanent income per household \( (Y/H) \), change in permanent income per household \( (\Delta Y/H) \), last year's auto ownership per driving age adult \( (A_{t-1}/(DPOT)) \) or per household \( (A_{t-1}/H) \), and the strike dummy variable \( (ST) \).
range of past estimates. In the equations normalized with driving age population, the own price elasticity with used car prices constant is between -1.6 and -1.7. In those normalized households, it is between -1.3 and -1.45.

Our estimates of the elasticity of new car sales with respect to used car prices are around one. Wykoff's are between 2.06 and 2.16. Wykoff used much different measures of new car and used car prices; aside from this, we cannot account for the difference in the estimates. In contrast, our estimate of the own price elasticity of used car demand is low. In the equations normalized with driving age population, it is between -0.65 and -0.80; in the ones normalized with total households, it is between -0.4 and -0.5.

The cross-elasticities of used car demand with respect to new car price and with respect to gasoline price are different in the used car demand equations normalized with driving age population and in the ones normalized with total households. They are higher in the ones normalized with driving age population. Below we will suggest why we are getting higher elasticities.

In the used car price equation, the elasticities of real used car prices with respect to real new car prices is greater than one. In the equations normalized with driving age population, this elasticity is between 1.45 and 1.65; in the ones normalized with households, it is between 1.35 and 1.50. These values do not mean that a dollar increase in average new car prices would result in more than a dollar's increase in average used car prices. Our measures of new car and used car prices are indices; the used car image reflects the retail prices of cars two to five years old. The average price of used cars covered in its index is about one-third of the average price of new cars covered in its in-

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For the moment, assume that new car prices average $3000 and used car prices average $1000. Also assume that average new car prices increase 10 percent, or $300. An elasticity of used car prices with respect to new car prices of 1.5 would mean that average used car prices would increase 15 percent, or $150. New car prices would then average $3300 and used car prices would average $1150. In this example, average used car prices increase 50 cents for every dollar increase in average new car prices, even though the elasticity of used car prices with respect to new car prices is 1.5.

Finally, normalizing with driving age population rather than total households makes a difference. Normalizing with driving age population improves the new car sales equation; the amount of the total variation in new car sales explained in the equation is larger and the equation's significance is greater.

Also, when we normalize with driving age population, the price elasticities are larger. The larger elasticities might be due to demographic changes during the estimation period—1954 to 1972—when the ratio of driving age population to total households fell from 2.1 to 1.9. New car sales and used car ownership generally rose. Thus, when normalized with driving age population, these variables show greater variation than when normalized with total households. The greater variation could be the reason for the higher elasticities. Which set of elasticities are closer to the truth depends on whether new car sales and used car ownership are more closely related to driving age population or to total households.

**COMPARISON WITH PREVIOUS WORK**

To compare our results with those of earlier studies, we must express our results in comparable terms. To do this, we calculated a series of overall elasticities. Our immediate concern here is with

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11 This information was gained in phone conversations with officials of the U.S. Department of Labor's Bureau of Labor Statistics.
total automobile ownership and new car sales, for both of which we calculated overall elasticities with respect to gasoline price, new car price, and permanent income. We did so by substituting the used car price equation in the new car demand and used car demand equations.

Here we deal only with the linear equations. A nonlinearity in the system keeps us from easily evaluating the overall elasticity of automobile ownership with the logarithmic equations. Following common practice, the elasticities are evaluated at sample means.

The elasticities can be seen in Table 15. There the symbol "E" stands for elasticity, e.g., \( E^A_P \) means the overall elasticity of automobile ownership with respect to gasoline price.

<table>
<thead>
<tr>
<th>Normalization</th>
<th>Estimation Technique</th>
<th>Gasoline Price</th>
<th>( E^A_P )</th>
<th>( E^A_P )</th>
<th>( E^A_P )</th>
<th>( E^A_P )</th>
<th>( E^A_P )</th>
<th>( E^A_P )</th>
</tr>
</thead>
<tbody>
<tr>
<td>DPOP</td>
<td>OLS</td>
<td>Per gallon</td>
<td>-0.54</td>
<td>0.23</td>
<td>0.93</td>
<td>-0.70</td>
<td>-0.12</td>
<td>6.75</td>
</tr>
<tr>
<td>DPOP</td>
<td>TSLS</td>
<td>Per gallon</td>
<td>-0.26</td>
<td>0.09</td>
<td>0.86</td>
<td>-0.86</td>
<td>-0.08</td>
<td>6.97</td>
</tr>
<tr>
<td>DPOP</td>
<td>TSLS</td>
<td>Per mile</td>
<td>-0.40</td>
<td>0.11</td>
<td>1.10</td>
<td>-0.97</td>
<td>-0.13</td>
<td>6.88</td>
</tr>
<tr>
<td>H</td>
<td>OLS</td>
<td>Per gallon</td>
<td>-0.34</td>
<td>0.09</td>
<td>1.34</td>
<td>-0.56</td>
<td>-0.32</td>
<td>7.29</td>
</tr>
<tr>
<td>H</td>
<td>TSLS</td>
<td>Per gallon</td>
<td>-0.24</td>
<td>0.07</td>
<td>0.95</td>
<td>-0.67</td>
<td>-0.13</td>
<td>7.56</td>
</tr>
<tr>
<td>H</td>
<td>TSLS</td>
<td>Per mile</td>
<td>-0.28</td>
<td>0.06</td>
<td>1.08</td>
<td>-0.72</td>
<td>-0.18</td>
<td>7.40</td>
</tr>
</tbody>
</table>

\( ^\alpha \) Evaluated at sample means.

Our estimates of the overall elasticity of automobile ownership with respect to gasoline prices are between -0.24 and -0.54. The higher estimates are probably misleading; they result from sets of equations that either are estimated with Ordinary Least Squares or use gasoline price per mile. Simultaneous equation bias probably affects elasticities
from equation sets estimated with Ordinary Least Squares. The elasticities from equations estimated with gasoline price per mile fail to consider offsetting adjustments in average automobile fuel efficiency. In the last section, we argued that the elasticity of auto fuel efficiency with respect to gasoline price is about 0.2. If an offsetting adjustment of this size occurs the following year, these elasticities would be reduced to between -0.10 and -0.2. With these considerations in mind, we conclude that the elasticity of automobile ownership with respect to real gasoline price is probably between -0.10 and -0.30.

Our overall elasticity of automobile ownership with respect to new car price is slightly positive. This result is bizarre. It means that new car units sold fall less rapidly than cars scrapped in response to higher new car prices. This result runs counter to the results of other recent studies, which assume a fixed rate of scrappage; these studies imply that an increase in new car prices would result in a decline in automobile ownership as new car sales fell. While we are not confident in our result, we can suggest a reason why this elasticity might be positive; it lies outside the formal model. Used cars are typically driven fewer miles than new cars; thus, for Americans to drive the same number of miles, more automobiles would be needed when an increase in new car prices shifts demands to the used car market.

The elasticity of automobile ownership with respect to permanent income per household appears to be slightly less than one. This result seems reasonable.

Our elasticities of new car units sold with respect to gasoline price are high. If we consider only the equation sets estimated with Two Stage Least Squares, they are between -0.65 and -1.0. Our results agree with those of Chase Econometric Associates and are counter to those of the Transportation Systems Center and the Federal Energy Administration. See our discussion of related research above.

When the feedback through used car price is included, the own price elasticity of new car demand drops drastically. Recall that the own price elasticity of new car demand, with used car prices constant, is between -1.6 and -1.7 when the new car demand equation is normalized.
with driving age population, and is between -1.3 and -1.45 when it is normalized with total households. In the equations estimated with Two Stage Least Squares, the own price elasticity of new car demand is close to zero when the feedback through used car prices is included. This elasticity is much lower than the ones estimated by Chase Econometric Associates and the Transportation Systems Center. Indeed, our elasticities are the lowest ones we know of.

Our elasticity estimates of new car sales with respect to permanent income are between 6.75 and 7.75. Compared with other estimates of income elasticity, these are high. However, most other studies have used current income or expenditures as their measures of income. We used permanent income; it is a weighted average of current income for eleven years. Permanent income fluctuates less from year to year than does current income; consequently, it is not surprising that our elasticity estimate is higher.

TOTAL ELASTICITIES

In Sec. II we discussed short-run elasticities; we were concerned with sorting out changes in fuel use due to miles driven per vehicle and to driving habits. In this section we have been concerned with changes in the automobile stock. Here, we bring the results of the two sections together; we can now see the long-run effect of higher gasoline prices on automobile gasoline use. See Table 16. For this summary table, we have used our short-run automobile equations with gasoline as the dependent variable. Our automobile stock equations are estimated with Two Stage Least Squares and with gasoline price per gallon--not price per mile--as the relevant variable. Elasticities from linear equations are evaluated at their sample means.

Our total own price elasticities of automobile gasoline use are -0.64 and -0.68 with form A short-run equations; they are -0.50 and -0.60 with form B. In both cases, more than half of the change in automobile gasoline use would occur in the short run. Form B equations result in lower overall elasticities because three component elasticities are lower: the own price elasticity of gasoline use (miles per gallon constant), the gasoline price elasticity of miles per gallon, and the automobile ownership elasticity of gasoline use.
Table 16
LONG-RUN PRICE ELASTICITIES OF AUTOMOBILE GASOLINE USE
WITH RESPECT TO REAL GASOLINE PRICE

<table>
<thead>
<tr>
<th>Form</th>
<th>Normalization</th>
<th>Change in Miles Driven</th>
<th>Change in Driving Habits</th>
<th>Change in Long-Run Automobile Ownership</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>DPOP</td>
<td>-0.31</td>
<td>-0.12</td>
<td>-0.25</td>
<td>-0.68</td>
</tr>
<tr>
<td>A</td>
<td>H</td>
<td>-0.29</td>
<td>-0.12</td>
<td>-0.23</td>
<td>-0.64</td>
</tr>
<tr>
<td>B</td>
<td>DPOP</td>
<td>-0.37</td>
<td>-0.06</td>
<td>-0.17</td>
<td>-0.60</td>
</tr>
<tr>
<td>B</td>
<td>H</td>
<td>-0.25</td>
<td>-0.07</td>
<td>-0.18</td>
<td>-0.50</td>
</tr>
</tbody>
</table>

NOTE: Wildhorn et al., op. cit., report a larger total long-run elasticity of -0.92 (see Table 6.2, p. 63). The numbers in the above table reflect elasticity estimates based on regression results that we have revised since the earlier report. The difference is due to two factors. One factor, which is relevant to both form A and form B, is a lower gasoline price elasticity of automobile ownership; the difference is attributed to a change in estimation technique to TSLS for the automobile stock equations. The second factor is the lower elasticity estimates with form B equations.
IV. CONCLUSIONS

We end this report with a series of conclusions concerning what is now known and what is still to be learned about the demand for highway motor fuel. These conclusions are divided into two parts. First, we summarize the results of our research and compare them with those of related studies. Second, we offer comments on a number of issues closely related to those directly addressed in this study. We believe that the sum of these two parts represents the current state of knowledge on this subject, and should be useful to decisionmakers concerned with formulating energy policy in the future. It should also serve as a guide for further research.

1. The short-run elasticity of highway motor fuel use with respect to real fuel price is low; our estimate is -0.26. Most estimates from other studies are between -0.1 and -0.3. This range of results seems to hold regardless of how the model is formulated or what data base is used.

2. In the first year after a fuel price change, about 80 percent of the price-induced change in highway fuel use (and automobile gasoline use) would be due to driving fewer miles. The rest would be due to changes in driving habits. This conclusion comes from our analysis in Sec. II. Using pooled time-series data from states, we estimated the total short-run price elasticity of highway motor fuel use to be -0.26; of this adjustment, 82 percent is due to changes in vehicle miles driven. In our analysis of short-run automobile gasoline use, our estimates of the total first-year price elasticity are between -0.38 and -0.43, when the dependent variable is automobile gasoline use (rather than automobile miles traveled). Depending on which equation is used, 67 to 73 percent of the total adjustment is due to change in automobile miles traveled.

3. After consumers have had time to fully adjust to a price change, the elasticity of highway motor fuel use (or automobile gasoline use) is
much higher; our estimate is between -0.64 and -0.88. Estimates of
the long-run price elasticity vary more than estimates of the short-
run price elasticity. However, the majority of long-run estimates
fall between -0.65 and -0.85; these include the long-run estimates of
Phils, Houthakker and Kennedy, Ramsey et al., and Sweeney. When our
results for the short-run and the long-run adjustment are considered
together, they are consistent with the lower (in absolute value) es-
timates of others.

4. If not offset by improved automobile fuel efficiency, a 10
percent increase in real gasoline price would result in a 2 to 3 per-
cent reduction in automobile ownership. We estimate the long-run elas-
ticity of automobile ownership with regard to real gasoline price to
be about -0.25, after we adjust for changes in average automobile fuel
efficiency in the first year. As we noted above, our analysis does not
include the effect of changes in new car fuel efficiency beyond one year.
The FEA's analysis does include the effect of longer-term changes in new
car fuel efficiency. It finds that improved new car fuel efficiency
would offset most of the decline in auto ownership due to higher gasoline
prices.\footnote{Sweeney, op. cit., p. 13.}

5. A given percentage increase in average motor vehicle fuel effi-
ciency would not result in an equal percentage decrease in highway motor
fuel use. The percentage decrease would be less. An increase in average
motor vehicle fuel efficiency (due perhaps to a fuel efficiency standard
for new cars) lowers the fuel cost of driving per mile; consequently, all
else equal, motorists would drive more. We estimate that a 10 percent
increase in average motor vehicle miles per gallon would result in a 7 to
8 percent saving in highway motor fuel use.

6. Higher gasoline prices would initially reduce new car sales, but
the reduction would be transitory.\footnote{This conclusion is based partially on findings presented in an earlier report (of which we were coauthors) where we use our models to forecast new car sales response to fuel price increases over the twenty-year period from 1975 to 1995. See Wildhorne et al., op. cit.} Most studies agree that the negative
effect of higher real gasoline prices on new car sales would last only two or three years, but there is little agreement over the size of the effect. Both TSC and FEA have estimated the elasticity of new car sales with respect to real gasoline price to be between -0.2 and -0.3. Chase Econometric's and our estimates are higher; they are between -0.65 and -1.0.

7. If new car sales taxes—graduated by fuel efficiency or weight—were levied and if they resulted in higher average new car prices, these taxes would slow the rate at which older, less efficient cars were replaced by newer, more efficient ones. This slower replacement rate would reduce the effectiveness of graduated taxes as a way of increasing average auto fuel efficiency. This conclusion is drawn from our analysis in Sec. III. We found that higher new car prices would increase the demand for used cars; consequently, used cars would be kept longer before being scrapped. If used cars are less fuel efficient than the new cars that replace them, higher new car prices would reduce the rate at which more efficient new cars replace less efficient used ones.

The following comments deal primarily with the likely effects of changes in new car fuel efficiency resulting from higher fuel prices. Since our study did not consider this issue directly, these conclusions are drawn from what we know about the findings of other research.

- An increase in average new car fuel efficiency would increase total new car sales if the price, performance, and comfort of new cars did not change. Work done by both TSC and FEA supports this conclusion. However, little is known about what would happen if performance and comfort were also to change; our analysis does not address this issue. All econometric work done to date has tacitly assumed that the performance and comfort of future new cars would be the same as new cars in the past; consequently, little can be said about what would happen if these characteristics are altered.

- A theoretical case can be made that, if the average fuel efficiency of new cars increases, new car buyers would shift their
purchases to larger new cars; this shift would partially offset the improvement in average new car fuel efficiency. Both TSC and FEA make such a case based on economic theory. Then, they appear to incorporate this shift into their forecasts by assumption without having actually derived estimates of its size.*

However, very little concrete evidence regarding shifts in new car sales between weight classes is currently available and further research on this question is necessary.

There is little agreement about how a reduction in automobile gasoline use due to fuel price increases would be divided among (1) less driving, (2) changed driving habits, and (3) ownership of more efficient cars in the long run. This is not surprising since no study has examined all three adjustment processes. In particular, the changes in both the size and characteristics of the long-run automobile stock have not been modelled completely. We noted that the studies by Chase Econometric Associates, TSC, and the FEA did not consider the effects of scrappage-rate changes on the long-run stock of automobiles. We considered the effects of auto scrappage rates in our long-run analysis; however, we did not consider the long-run effect of changes in new car fuel efficiency. Consequently, further work is necessary before the different adjustment processes are fully understood.

Our ability to forecast how large an increase in new car fuel efficiency would result from graduated taxes on new cars is limited because no one has studied the response of automobile makers. All recent studies have considered only the demand for new cars. If the goal is to forecast future market conditions, however, we must consider both the demand and the supply of new cars.

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Appendix A

DATA FOR NATIONAL TIME-SERIES ANALYSIS

So that others might verify our results, we give here the data series used in our national time-series analysis. Sections II and III discuss where we got the data and how we revised them. We omit the data used in our pooled state time-series analysis because of the large amount of data and the high cost of publication.
<table>
<thead>
<tr>
<th>Year</th>
<th>Population (P) (000)</th>
<th>Driving Age Population (DPOP) (000)</th>
<th>Households (H) (000)</th>
<th>Automobile Miles Traveled (V) (000)</th>
<th>Automobile Gasoline Used (F) (000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1954</td>
<td>161,884</td>
<td>98,717</td>
<td>46,893</td>
<td>448,996</td>
<td>30,901</td>
</tr>
<tr>
<td>1955</td>
<td>165,069</td>
<td>99,636</td>
<td>47,874</td>
<td>485,901</td>
<td>33,534</td>
</tr>
<tr>
<td>1956</td>
<td>168,088</td>
<td>100,483</td>
<td>48,785</td>
<td>505,423</td>
<td>35,295</td>
</tr>
<tr>
<td>1957</td>
<td>171,187</td>
<td>101,377</td>
<td>49,543</td>
<td>527,470</td>
<td>36,732</td>
</tr>
<tr>
<td>1958</td>
<td>174,149</td>
<td>102,313</td>
<td>50,402</td>
<td>542,801</td>
<td>38,065</td>
</tr>
<tr>
<td>1959</td>
<td>177,135</td>
<td>103,606</td>
<td>51,302</td>
<td>570,729</td>
<td>40,023</td>
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<tr>
<td>1960</td>
<td>179,975</td>
<td>104,763</td>
<td>52,799</td>
<td>585,801</td>
<td>41,138</td>
</tr>
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<td>1961</td>
<td>182,973</td>
<td>105,905</td>
<td>53,464</td>
<td>602,189</td>
<td>41,994</td>
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<td>1962</td>
<td>185,738</td>
<td>107,505</td>
<td>54,652</td>
<td>626,472</td>
<td>43,718</td>
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<td>1963</td>
<td>188,438</td>
<td>108,691</td>
<td>55,189</td>
<td>646,144</td>
<td>45,190</td>
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<tr>
<td>1964</td>
<td>191,085</td>
<td>110,867</td>
<td>55,996</td>
<td>673,550</td>
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<tr>
<td>1965</td>
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<td>112,671</td>
<td>57,251</td>
<td>706,386</td>
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<tr>
<td>1966</td>
<td>195,501</td>
<td>114,349</td>
<td>58,092</td>
<td>744,844</td>
<td>53,203</td>
</tr>
<tr>
<td>1967</td>
<td>197,374</td>
<td>116,095</td>
<td>58,845</td>
<td>766,466</td>
<td>55,023</td>
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<tr>
<td>1968</td>
<td>199,312</td>
<td>117,993</td>
<td>60,444</td>
<td>805,693</td>
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<tr>
<td>1970</td>
<td>203,805</td>
<td>122,222</td>
<td>62,874</td>
<td>890,844</td>
<td>65,648</td>
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<tr>
<td>1971</td>
<td>206,256</td>
<td>124,455</td>
<td>64,374</td>
<td>939,102</td>
<td>69,204</td>
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<tr>
<td>1972</td>
<td>208,232</td>
<td>126,647</td>
<td>66,676</td>
<td>986,407</td>
<td>73,121</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>Automobile Stock (A) (000)</th>
<th>New Car Sales (N) (000)</th>
<th>Adjusted Consumer Price Index (ACPI)</th>
<th>Real New Car Price (P_n)</th>
<th>Real Used Car Price (P_u)</th>
<th>Real Gasoline Price (P_g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1954</td>
<td>48,499</td>
<td>5,400</td>
<td>0.932</td>
<td>0.996</td>
<td>1.015</td>
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<td>0.963</td>
<td>0.960</td>
<td>1.012</td>
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<td>1956</td>
<td>54,201</td>
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<td>0.945</td>
<td>0.974</td>
<td>0.911</td>
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<td>1957</td>
<td>55,906</td>
<td>6,200</td>
<td>0.974</td>
<td>0.995</td>
<td>0.990</td>
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</tr>
<tr>
<td>1958</td>
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<td>4,600</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>1959</td>
<td>59,562</td>
<td>6,200</td>
<td>1.004</td>
<td>1.039</td>
<td>1.113</td>
<td>1.008</td>
</tr>
<tr>
<td>1960</td>
<td>61,684</td>
<td>7,000</td>
<td>1.030</td>
<td>0.995</td>
<td>0.986</td>
<td>1.003</td>
</tr>
<tr>
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<td>63,275</td>
<td>5,700</td>
<td>1.041</td>
<td>0.985</td>
<td>1.014</td>
<td>0.981</td>
</tr>
<tr>
<td>1962</td>
<td>65,929</td>
<td>7,100</td>
<td>1.052</td>
<td>0.971</td>
<td>1.096</td>
<td>0.976</td>
</tr>
<tr>
<td>1963</td>
<td>69,027</td>
<td>7,900</td>
<td>1.066</td>
<td>0.952</td>
<td>1.094</td>
<td>0.962</td>
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<td>0.938</td>
<td>1.127</td>
<td>0.946</td>
</tr>
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<td>1965</td>
<td>75,261</td>
<td>9,700</td>
<td>1.097</td>
<td>0.902</td>
<td>0.966</td>
<td>0.966</td>
</tr>
<tr>
<td>1966</td>
<td>78,354</td>
<td>9,300</td>
<td>1.132</td>
<td>0.859</td>
<td>1.041</td>
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Appendix B

DERIVATION OF ELASTICITIES

In Section II we presented some derived elasticity relationships between fuel use and vehicle miles traveled. This Appendix presents details of the derivations.

RELATIONSHIPS BETWEEN ELASTICITIES

Equation (2.5) is our basic demand function for fuel. We can use it to get a demand function for vehicle miles traveled. By definition, vehicle miles traveled by the family is equal to fuel used multiplied by miles per gallon of fuel, or

\[ V \equiv F(P_f, M(P_f), Y, A) \cdot M(P_f) \quad \text{(B.1)} \]

In other words, the demand function for vehicle miles has the same arguments as the expression on the right, or

\[ V(P_f, M(P_f), Y, A) \equiv F(P_f, M(P_f), Y, A) \cdot M(P_f) \quad \text{(B.2)} \]

We can use this identity to prove some propositions that are useful in sorting out the scale effect and the substitution effect. First, we show that the elasticity of vehicle miles with respect to the fuel price, holding miles per gallon of fuel constant, equals the elasticity of fuel use with respect to the fuel price, miles per gallon of fuel constant. Differentiating Eq. (B.2),

\[
\frac{\partial V}{\partial P_f} \bigg|_{M=C} \equiv \frac{\partial F}{\partial P_f} \bigg|_{M=C} \cdot M \\
\frac{\partial V}{\partial P_f} \bigg|_{M=C} \equiv \frac{P_f}{V} \frac{\partial F}{\partial P_f} \bigg|_{M=C} \cdot \frac{P_f}{V} \cdot M \\
= \frac{\partial F}{\partial P_f} \bigg|_{M=C} \cdot \frac{P_f}{F \cdot M} \cdot M \text{ since } V = F \cdot M \quad \text{(B.3)}
\]
\[
\frac{\partial V}{\partial M} \bigg|_{P_f = C} = \frac{\partial F}{\partial P_f} \bigg|_{M = C} \cdot \frac{P_f}{F} \\
\text{or} \quad E^V_{P_f} \bigg|_{M = C} = E^F_{P_f} \bigg|_{M = C}
\]

Next, the elasticity of vehicle miles with respect to an autonomous change in miles per gallon, fuel price constant, is equal to one plus the elasticity of fuel use with respect to an autonomous change in miles per gallon of fuel used, fuel price constant. Differentiating,

\[
\begin{align*}
\frac{\partial V}{\partial M} \bigg|_{P_f = C} &= \frac{\partial F}{\partial M} \bigg|_{P_f = C} \cdot M + F \\
\frac{\partial V}{\partial M} \bigg|_{P_f = C} &= \frac{\partial F}{\partial M} \bigg|_{P_f = C} \cdot \frac{M}{V} + F \cdot \frac{M}{V} \\
&= \frac{\partial F}{\partial M} \bigg|_{P_f = C} \cdot \frac{M}{F \cdot M} \cdot M + \frac{F}{F} \cdot \frac{M}{M} \quad \text{since} \quad V = F \cdot M \quad (B.4) \\
&= \frac{\partial F}{\partial M} \bigg|_{P_f = C} \cdot \frac{M}{F} + 1 \\
&= 1 \quad + \frac{\partial F}{\partial M} \bigg|_{P_f = C} \cdot \frac{M}{F}
\end{align*}
\]

or

\[
E^V_M = E^F_M + 1
\]

The interpretation of this relationship is straightforward. For example, if a 100 percent increase in miles per gallon results in only an 80 percent reduction in fuel use, vehicle miles traveled must increase by 20 percent.
Now, the total elasticity of vehicle miles with respect to the price of gasoline equals the elasticity of fuel use with respect to the fuel price, miles per gallon of fuel constant, plus the quantity one plus the elasticity of fuel use with respect to an autonomous change in miles per gallon, fuel price constant, multiplied by the elasticity of miles per gallon of fuel used with respect to the price of fuel. Totally differentiating Eq. (B.2),

\[
\frac{dV}{dP_f} = \left. \frac{\partial V}{\partial P_f} \right|_{M=C} + \left. \frac{\partial V}{\partial M} \cdot \frac{dM}{dP_f} \right|_{M=C} \left( \frac{\partial F}{\partial P_f} \right)_{M+F} + \left. \frac{\partial F}{\partial M} \cdot \frac{3M}{\partial P_f} \right|_{M+C} \] 

\[
\frac{dV}{dP_f} \cdot \frac{P_f}{V} = \left. \frac{\partial V}{\partial P_f} \right|_{M=C} \cdot \frac{P_f}{V} + \left. \frac{\partial V}{\partial M} \cdot \frac{1}{V} \cdot \frac{dM}{dP_f} \right|_{M=C} \cdot \frac{P_f}{V} + \left. \frac{\partial F}{\partial P_f} \right|_{M=C} + \frac{F}{M} \cdot \left. \frac{dM}{dP_f} \right|_{M=C} \cdot \frac{P_f}{V} 

\]

since \( V \equiv F \cdot M \)

\[
\frac{dV}{dP_f} = \left. \frac{\partial V}{\partial P_f} \right|_{M=C} \cdot \frac{P_f}{V} + \left. \frac{\partial V}{\partial M} \cdot \frac{M}{V} \right|_{M=C} \cdot \frac{P_f}{M} + \left. \frac{\partial F}{\partial P_f} \right|_{M=C} + \frac{F}{M} \cdot \left. \frac{dM}{dP_f} \right|_{M=C} \cdot \frac{P_f}{V} + \left. \frac{\partial F}{\partial M} \cdot \frac{M}{F} \right|_{M=C} \cdot \frac{P_f}{V} 

\]

\[
\left( \frac{dM}{dP_f} \cdot \frac{P_f}{M} \right) + \frac{dM}{dP_f} \cdot \frac{P_f}{M} 
\]
Rewriting,

\[
E_P^V \equiv E_P^V \bigg|_{M=C} + E_M^V \cdot E_P^M \equiv E_P^F \bigg|_{M=C} + E_M^F \cdot E_P^M + E_P^M
\]

\[
e_P^V \bigg|_{M=C} + E_M^V \cdot E_P^M \equiv E_P^F + (1 + E_M^F) \cdot E_P^M \quad (B.5)
\]

Here we see that the total elasticity of vehicle miles traveled with respect to fuel price is the sum of two offsetting effects. The scale effect, as presented by \( E_P^V \bigg|_{M=C} \), will be offset by the product of the elasticity of vehicle miles traveled with respect to fuel efficiency, \( E_M^V \), and the elasticity of fuel efficiency with respect to fuel price.

We can derive similar results for fuel use elasticities. We rewrite Eq. (B.2) as:

\[
F(P_f, M(P_f), Y, A) \equiv V(P_f, M(P_f), Y, A)^{-1}(P_f)
\]

When we differentiate this expression, we get partial elasticities identical to Eqs. (B.3) and (B.4); we will not derive these results again. However, it will be useful to derive the total elasticity of fuel use with respect to its price. Differentiating,

\[
\frac{dF}{dP_f} \equiv \frac{\partial F}{\partial P_f} \bigg|_{M=C} + \frac{\partial F}{\partial M} \cdot \frac{dM}{dP_f} \equiv \left[ \frac{\partial V}{\partial P_f} \bigg|_{M=C} + \frac{\partial V}{\partial M} \cdot \frac{dM}{dP_f} \right] - VM^{-2} \frac{\partial M}{\partial P_f}
\]
\[
\frac{dF}{dF} \cdot \frac{P_f}{F} = \frac{\partial F}{\partial M} \bigg|_{M=C} \cdot \frac{P_f}{F} + \left( \frac{\partial F}{\partial V} \cdot \frac{1}{F} \right) \left( \frac{\partial M}{\partial P_f} \cdot P_f \right) = \frac{V}{P_f} \bigg|_{M=C} + \frac{\partial V}{\partial M} \cdot \frac{\partial M}{\partial P_f} \frac{P_f}{M} - \frac{3M}{\partial P_f} \frac{P_f}{M}
\]

\[
E_p^E = E_p^F \bigg|_{M=C} + E_M^F \cdot E_p^M = E_p^V \bigg|_{M=C} + E_M^V \cdot E_p^M - E_p^M
\]

\[
E_p^F = E_p^F \bigg|_{M=C} + E_M^F \cdot E_p^M = E_p^V \bigg|_{M=C} + \left( E_M^V \bigg|_{P=C} - 1 \right) E_p^M
\] (B.6)

In other words, the total elasticity of fuel use with respect to its price has two parts. One is the elasticity of vehicle miles with respect to the fuel price, miles per gallon constant; the other is the elasticity of miles per gallon with respect to the price of fuel multiplied by the elasticity of vehicle miles with respect to miles per gallon, fuel price constant, minus one. The first part of this expression stands for the scale effect; the second, for the substitution effect. If families can substitute travel time (and other inputs) for fuel, the percentage reduction in fuel used due to a fuel price increase will be greater than the percentage reduction in travel. However, the difference will be less than the percentage increase in miles per gallon. It will be less because the increase in miles per gallon reduces the cost of fuel per mile. Thus, the increase in miles per gallon partially offsets the initial increase in gasoline price.

In the text, we made a final point: The elasticity of vehicle miles with respect to fuel price, miles per gallon constant, equals the negative of the elasticity of vehicle miles with respect to miles per gallon, the price of fuel constant. This can be seen in the following set of equalities.
\[
\frac{\partial V}{\partial P_f} \bigg|_{M=C} = \frac{\partial V}{\partial P_f} \bigg|_{V=M=C} = \frac{\partial V}{\partial (P_f|M)} \frac{P_f|M}{V} \bigg|_{P_f=C} = \frac{\partial V}{\partial 1/M} \frac{1/M}{V} \bigg|_{P_f=C} = \frac{\partial V}{\partial M} \frac{M}{V} \bigg|_{P_f=C} \\
= \frac{V}{M} \bigg|_{P_f=C}
\]

(B.7)

In other words, an increase in the price of fuel per gallon, or a decrease in miles per gallon that has the same effect on the price of fuel per mile, will have the same effect on vehicle miles driven.
BIBLIOGRAPHY


Schim van Loeff, S., and R. Harkema, "A Note on Aggregation of CES-Type Production Functions," Netherlands School of Economics, unpublished paper, n.d.


