The demand for energy in the transport sector in the United States

By Noel D. Uri*

The transport sector uses energy to move people and goods by highway and air. In the United States, the transport sector accounted in 1978 for 26% of total energy consumption. Given the likelihood that this will increase as the level of economic activity expands (see Table 1 for an indication of the trend since 1965), it becomes essential to investigate whether there are factors that will serve to mitigate against this trend. In particular, will increases in the price of energy affect the use of transport? Is there an identifiable substitution between energy sources used for transport?

One of the characteristics of the transport sector in the United States is that the type of energy used is closely related to the transport mode (or vehicle), which, in turn, provides well-defined transport services. For example, diesel fuel is consumed by motor carriers who provide a transport service (surface cargo transport) that is different from other modes. Given a specific piece of capital equipment used in the transport process, there is little, and for the most part no, possibility of change of fuel. Jet airplanes do not run on electrical energy. Where interfuel substitution occurs, it will be the result of capital stock substitution (e.g., automobiles powered by diesel fuel instead of by motor gasoline), or switching modes of travel (e.g., using motor gasoline instead of electrical energy by using an automobile instead of taking a subway on the journey to work).

These institutional and technological rigidities would suggest that interfuel substitution would be fairly limited in the transport sector. Motor gasoline, diesel fuel used for motor vehicles, aviation (jet) fuel, and electrical energy (used in rail travel and by electric vehicles) are typically associated with capital equipment that is not designed for multifuel use.1

The constrained possibility of interfuel substitution will not necessarily preclude changes in the demand for energy in response to variations in relative price. Instead, capital and/or labour can be substituted for energy. Thus, capital can be substituted for energy through improved energy efficiency (e.g., by smaller and lighter vehicles), and labour can be substituted for energy through the manual mode (e.g., walking).

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1 The use of electrical energy by vehicles accounted for less than 0.1% of total generation in 1978. See, e.g., Glixon (1981).
The expenditure distribution in the transport sector for various energy forms (motor gasoline, diesel fuel, jet fuel, and electrical energy) is given in Table 1 for the United States as a whole over the period 1965 through 1978. Motor gasoline is predominant. It accounted for 96% of transport energy expenditures in 1965. This fell to 87% in 1978. Diesel fuel and jet fuel are distant seconds, though they have both made significant inroads into transport energy expenditures over the past decade. Note that diesel fuel is used primarily by buses and trucks, while motor gasoline is used by automobiles. There is some possibility of interfuel substitution between motor gasoline and diesel fuel. Some automobiles use diesel fuel, while some trucks consume motor gasoline. Moreover, bus travel is a substitute for automobile travel. This must be examined empirically.

Jet fuel consumption has grown rapidly, reflecting the steady increase in air travel. One would expect this trend to continue in light of the deregulation of airlines (Bailey, 1978). The use of electrical energy is relatively small (but not insignificant). There is a very real potential for interfuel substitution between electrical energy and other energy sources. Trains can be powered by diesel engines as well as by electric turbines.

The components of energy demand in the transport sector are examined in the light of the foregoing considerations. The next three sections study the demand for motor gasoline, diesel fuel and aviation (jet) fuel. It is realised that there is endless variety of transport modes and capital equipment. The notion of an energy aggregate

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\(^2\) Note that, while it might be desirable to report regional data, conformable times series do not exist.
is unsuitable. Therefore the total demand for each energy source is investigated separately. After this determination of the aggregate energy demand, the extent of interfuel substitution over the historical period is modelled. This should help us to see whether changing relative energy prices are affecting energy demand.

DEMAND FOR MOTOR GASOLINE

Background

Undoubtedly the most intensively investigated section of the demand for energy is motor gasoline. A plethora of studies exist. Typically, the studies use either time series analysis or pooled cross-section time series analysis, with price and income as explanatory variables. Short-run price elasticities range between−0.06 and−0.47, while long-run elasticities vary between−0.48 and−3.80. The income elasticities are somewhat less variable, ranging between 0.30 and 0.74 in the short run and 0.98 and 1.69 in the long run (see Taylor (1976) for a comment on these results).

These studies present problems that have the effect of biasing the price elasticity downward (in absolute terms). United States data over most of the sample periods employed show relatively small variations in the price of motor gasoline. Before the decade of the seventies the price of motor gasoline was relatively low, and automobiles (on a weight basis) were fairly inexpensive. The network of highways and roads, the spatial distribution of the population, and the stock of automobiles became adjusted to these attributes. Until the precipitous price increase in imported crude oil beginning in 1973, the automobile industry in the United States had not been wont to produce the smaller sized, more fuel-efficient, vehicles.

Furthermore, most (though not all) studies of the demand for motor gasoline have relied on single equation specifications. For example, Houthakker, Verlager and Sheehan (1974) determined the quantity demanded in the current period directly from the quantity demanded in the previous period, and price and income in the current period. This approach fails to reflect the role of the stock of automobiles and its characteristics (e.g., fuel efficiency) in modelling the demand for motor gasoline. Consequently, the adjustment process is obfuscated.

The model formulation

Following Cato, Rodekohr and Sweeney (1976), Griffin (1979) and Ramsey, Rasche and Allen (1975), the demand for motor gasoline consists of three components. These include the utilisation rate of an automobile (looked upon as an average across the entire fleet), $U$; the fuel efficiency, $Fe$; and the stock of vehicles, $S$. These are combined to yield motor gasoline demand in period $t$, $X_t$, in the following way:

$$X_t = U_t \cdot S/Fe.$$  \hspace{1cm} (1)

The advantage of examining the demand for motor gasoline in this fashion is that the short-run and long-run elements can be examined independently. Thus, factors affecting the utilisation of the existing stock of automobiles will affect motor gasoline
more quickly than factors affecting the average efficiency of the stock of automobiles.

The absence of regional data on all the relevant explanatory variables precludes a highly disaggregated (by state or region) estimation of the functional relationships. Consequently, a United States aggregate model is estimated. No attempt is made to disaggregate the data by size of vehicle.

The stock of cars is hypothesised to be a linear in logarithmic function of per capita disposable income, \( Y_r \), and a generalised price computed (following Cato, Rodenkohr and Sweeney) as:

\[
GP = P_s + \sum_{i=0}^{9} \frac{(P_m/MPG) \cdot VMi}{(1 + r)^i}
\]

where \( GP \) denotes the generalised price of cars, \( r \) denotes the discount rate (which is assumed, following Baumol (1968), to equal 10%), \( P_m \) denotes the price of motor gasoline, \( MPG \) denotes the average automobile efficiency for new automobiles, \( VM \) denotes the vehicle miles travelled per year (which is set equal to 10,000 miles per year, the U.S. national average (Staley, 1979), and \( P_s \) denotes the sticker price of cars. Finally, the demand for automobiles is expressed as:

\[
\log S_t = \alpha_0 + \alpha_1 \log Y_t + \alpha_2 \log GP_t
\]

where \( \alpha_0, \alpha_1 \) and \( \alpha_2 \) are parameters to be estimated, \( \log \) denotes Napierian logarithms, and the other notation is as previously defined.

This demand function implicitly assumes that consumers correctly discount the lifetime cost of motor gasoline for the operation of a vehicle. The total stock variable is constructed on the assumption of exponential scrappage. That is, the stock of automobiles in the current period is a function of the stock in the previous period and the current period new car sales:

\[
S_t = NCS_t + 0.92S_{t-1}
\]

where \( NCS \) denotes new car sales. Note that, following Sweeney (1975), the annual scrappage rate is estimated to be 8% per year. It is this definition of the stock of automobiles that is used in the estimation of relationship (3).

The utilisation of the automobile stock, or the vehicle miles travelled, is a function of, among other things, the cost per mile of travel, \( CPM \), income per capita, \( Y \), weather (measured as cooling degree days), \( W \), and the unemployment rate, \( RU \). This last factor is critical in reflecting the impact employment has on the journey to work, which in turn directly affects the utilisation of the existing vehicle stock. The inclusion of weather is important in view of the consumption of motor gasoline in warm weather. The cost per mile is constructed as a simple function of the real price of motor gasoline divided by the average number of miles per gallon of the existing vehicle stock. Thus, the cost per mile is just a function of the gasoline cost.

These considerations give a utilisation specification of the form:

\[
\log U_t = \beta_0 + \beta_1 CPM + \beta_2 Y_t + \beta_3 RU_t + \beta_4 W_t
\]

where \( \beta_0, \beta_1, \beta_2, \) and \( \beta_3 \) are parameters to be estimated, and the other notation is as previously defined.

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The estimation of fuel efficiency of the fleet is a straightforward process. Assuming exponential scrappage and usage rate, the average miles per gallon of the automobile stock in a given period is a function of last period's automobile stock, the scrappage rate, the utilisation rate, and the quantity and miles per gallon of new cars. The concept of adjusting the stock for relative usage reflects the fact that older cars are driven less. Consequently, if new car sales are relatively small, the automobile stock consists largely of older cars, and, assuming a declining utilisation rate, the stock will be used less than if it had relatively more new cars.

Data

The demand for motor gasoline is measured as the total consumption of motor gasoline. Data on the stock of motor vehicles variable, consisting of passenger car registrations, were obtained from the Federal Highway Administration. It must be realised that some motor gasoline is consumed by vehicles other than passenger cars (e.g., by trucks). It is not, unfortunately, possible to reflect this in the data. Motor gasoline price data came from Platts Oil Price Handbook. Data on vehicle miles travelled and efficiency of new automobiles were obtained from the Federal Highway Administration.

The sticker prices of cars came from Milne et al. (n.d.). Motor gasoline prices were obtained from the Department of Energy, and the information on the rate of unemployment came from the Bureau of Labor Statistics.

The per capita income variable is as reported by the Bureau of Economic Analysis. Note that it incorporates two separate influences. On the one hand, according to traditional neoclassical microeconomic theory, the level of income influences the demand for any good or service. On the other hand, it reflects such things as changes in the degree of urbanisation and a trend toward multiple car ownership.

All the data series cover the period 1964 through 1978. All pecuniary values are in constant (1972) dollar terms.

Estimation results

The two equations, equation (3) and equation (5), specified in the foregoing subsection were estimated by classical least squares, serial correlation being corrected for by the Cochrane and Orcutt (1945) iterative technique. The results for equation (3) are given in Table 2, and the results for equation (5) in Table 3.

The estimated values are consistent with a priori expectations. The stock of automobiles increases as per capita income increases. A 1% rise in per capita income causes a 1.22% rise in the stock of automobiles. This result is quite a bit smaller than the unrealistically high elasticity estimate of 5.2 obtained by Cato, Rodekohr and Sweeney (1976) for the United States. Unfortunately, there are few other studies by which this disparity can be judged. One study that does afford a comparative opportunity is that by Chow (1960). He finds income elasticities between 1.4 and 2.0 over the period 1929 through 1953; this is more consistent with the results obtained here. It is appropriate to question whether an income elasticity in excess of two is realistic for a relatively high-income country like the United States. The stock of automobiles is large, and the proportion of automobiles to the total popula-
Table 2

Stock of Automobiles

<table>
<thead>
<tr>
<th>Coefficient</th>
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<tr>
<td>$\alpha_0$</td>
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<tr>
<td></td>
<td>(1.6040)</td>
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<td>(0.5142)</td>
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<td>(0.2741)</td>
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<td>$\rho^b$</td>
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<td>D.W.$^c$</td>
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</table>

$^{a}$ Standard errors of estimates in parentheses.

$^{b}$ Serial correlation coefficient.

$^{c}$ Durbin–Watson statistic.

Table 3

Utilisation Rate of Automobiles

<table>
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<th>Coefficient</th>
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</thead>
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<td>(5.0173)</td>
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<td>$\beta_1$</td>
<td>-0.9743</td>
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<tr>
<td></td>
<td>(0.3188)</td>
</tr>
<tr>
<td>$\beta_2$</td>
<td>0.2621</td>
</tr>
<tr>
<td></td>
<td>(0.1193)</td>
</tr>
<tr>
<td>$\beta_3$</td>
<td>-0.0104</td>
</tr>
<tr>
<td></td>
<td>(0.0053)</td>
</tr>
<tr>
<td>$\beta_4$</td>
<td>0.0218</td>
</tr>
<tr>
<td></td>
<td>(0.0100)</td>
</tr>
<tr>
<td>$\rho^b$</td>
<td>0.6471</td>
</tr>
<tr>
<td></td>
<td>(0.3002)</td>
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<td>0.9546</td>
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<tr>
<td>D.W.$^c$</td>
<td>2.11</td>
</tr>
</tbody>
</table>

$^{a}$ Standard errors of estimates in parentheses.

$^{b}$ Serial correlation coefficient.

$^{c}$ Durbin–Watson statistic.

The estimate of the price elasticity is significant and of the correct sign, suggesting
that a 1% increase in the generalised price results in a 0.76% reduction in the stock of automobiles. This result is only slightly smaller than the −0.96 estimate of Cato, Rodekohr and Sweeney.

The utilisation equation yields interesting results. Most noticeable is the relatively high degree of responsiveness to changes in the price of motor gasoline. The suggestion is that a 1% rise in the price of motor gasoline will result in a −0.97% decline in miles travelled per vehicle. This estimate is almost precisely the same as the −0.92 value obtained by Wildhorn et al. (1974). Cato, Rodekohr and Sweeney (1976), on the other hand, obtain an estimate of −0.36. This seems to be rather low in the light of the Wildhorn et al. study and of the studies surveyed by Taylor (1976). In this latter group a value of −0.80 is the norm.

The income elasticity is positive and of approximately the same magnitude as the estimate obtained by the other studies cited. The one exception is that of Griffin (1979), who actually gets a negative estimate on the income term for the Organization for Economic Cooperation and Development (OECD) countries. He argues that income serves as a proxy for cars per capita, which should exert a negative influence on gasoline consumption. As income increases, cars per capita rise, and this, in turn, leads to lower consumption. The veracity of this argument is not judged here.

The significance of weather in explaining utilisation is insightful. The suggestion is that a 1% increase in growth leads to a 0.02% rise in vehicle miles travelled. This reflects the fact that automobiles are used more intensively in periods of very element weather. We must, however, add a caution that the weather variable does not include any correction for longer warm-ups during periods of cold weather, or for the operation of air conditioners in warmer periods. This would be reflected in the efficiency parameter.

Finally, the rate of unemployment proves to have small but quite significant influence. More than 50% of all motor gasoline is consumed on the journey to work (Kulash, 1978). Any interruption of that journey, as can be seen, serves to reduce the number of miles travelled, and thus to reduce the demand for motor gasoline.

What can one glean from the estimation results? The responsiveness of motor gasoline demand to change in the price of motor gasoline is quite significant. This response is shown on two fronts. First, it affects the utilisation of automobiles (in the form of vehicle miles travelled). Second, it effects the stock of automobiles, implicitly changing the characteristics of this stock (for example, toward more fuel efficiency).

DEMAND FOR DIESEL FUEL

Because of the amorphous composition of the group of consumers of diesel fuel, the determination of demand for diesel fuel is less refined. Lack of adequate data on the characteristics of consumers precludes a structure analogous to that used for determining the demand for motor gasoline.

The methodology adopted to model aggregate energy demand is the traditional formulation based on price and economic activity (Houthakker and Taylor, 1970). The appropriateness of these factors is embedded in economic theory. The focus of this investigation is on long-term relationships. (Note that, for this reason, no short-
run adjustment parameter is introduced.) As a result the approach used is that of Houthakker and Taylor (1970), which suggests that diesel fuel demand, \( D_r \), is a linear in logarithms function of the level of economic activity (measured by the index of industrial production in real terms), \( IP \). Economic activity is a principal determinant of freight movements. We introduce also the price of diesel fuel relative to the price of all goods and services, \( P_d \). In preliminary analyses, to make the results conformable to those in the previous section, weather and the rate of unemployment were introduced. Neither proved to be statistically significant. The exact functional specification is thus:

\[
\log D_r = \delta_0 + \delta_1 \log IP_t + \sum_{j=0}^{n} \delta_{2j} \log P_{d(j-1)}
\]  

(6)

where \( \delta_0, \delta_1, \) and \( \delta_{2j} \) are parameters to be estimated, and the other terms are as previously defined.

A priori one would expect the coefficient on the economic activity variable to be positive, suggesting that increases in freight and passenger movements, which vary coincidentally with industrial production, increase the demand for diesel fuel. It is a well understood phenomenon that changes in the price of diesel fuel will alter the utilisation of the existing stock of trucks and buses in the current period. Additionally, as the price of energy increases in relation to the price of capital (i.e., trucks and buses) there will be a replacement of existing (and implicitly less energy-efficient) trucks and buses by relatively more energy-efficient rolling stock. Since the replacement process is spread over a number of years, price changes in the current period would be expected to influence the demand for diesel fuel several years hence.

The data requirements to estimate relationship (6) are easily satisfied. Information on diesel fuel demand is available from the Department of Energy, and the prices are available from the Bureau of Labor Statistics. The measure of industrial production is that compiled by the Federal Reserve Board. To make the estimation horizon consistent with that for motor gasoline demand, the period 1964 through 1978 is used in the estimation.

The results are given in Table 4. Various lengths of lag were tried on the price variable, using the polynomial distributed lag technique of Almon (1965). A third order lag using a quadratic polynomial provided the best (in the statistical sense) fit. This is not meant to imply without reservation that the effects of a change in the price of diesel fuel are exhausted after three years, but only that the identifiable, measurable effect dissipates. Correction was required for serial correlation.

The importance of the level of economic activity in explaining the demand for diesel fuel is quite transparent. Diesel fuel is a normal good, and increased demand is closely linked to rising industrial production. The elasticity effectively suggests that as the level of economic activity doubles, the quantity of diesel fuel demanded doubles. This is almost equal to the 0.97 value Griffin (1979) reports for his eighteen-country OECD sample.

The diesel fuel price profile is quite significant. The effect of a price change in the current period is to reduce (increase) consumption in the current period by 0.15 for each 1% increase (decrease). The impact reaches its peak in the second period; then, for each 1% change in price in the current period, the quantity demanded falls in the next period by 0.22%. The aggregate effect of a change in price of 1% is to
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TABLE 4
Diesel Fuel Demand

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Estimate$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta_0$</td>
<td>-0.6171</td>
</tr>
<tr>
<td></td>
<td>(0.2547)</td>
</tr>
<tr>
<td>$\delta_1$</td>
<td>0.9955</td>
</tr>
<tr>
<td></td>
<td>(0.4203)</td>
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<td>$\delta_{30}$</td>
<td>-0.1536</td>
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<tr>
<td></td>
<td>(0.0774)</td>
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<tr>
<td>$\delta_{21}$</td>
<td>-0.2190</td>
</tr>
<tr>
<td></td>
<td>(0.1061)</td>
</tr>
<tr>
<td>$\delta_{22}$</td>
<td>-0.1839</td>
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<tr>
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<td>(0.0684)</td>
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<td>$\delta_{23}$</td>
<td>-0.0942</td>
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<tr>
<td></td>
<td>(0.0453)</td>
</tr>
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<td>$\rho^b$</td>
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<tr>
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<td>(0.1291)</td>
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<tr>
<td>$\bar{R}^2$</td>
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<td>D.W.$^c$</td>
<td>2.05</td>
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</table>

$^a$ Standard errors of estimates in parentheses.
$^b$ Serial correlation coefficient.
$^c$ Durbin-Watson statistic.

change the quantity demanded in the opposite direction by 0.65%. (Note that the lag structure results from the degree of the polynomial fit through the coefficients.) This value is consistent with the estimate obtained by the Federal Energy Administration (1976).

THE DEMAND FOR AVIATION FUEL

The aviation fuel component of total transport fuel expenditures is growing rapidly, and in 1978 was approximately equal in size to diesel fuel demand. From the early part of the 1960s, jet fuel began to be the dominant component of aviation gasoline as jet aircraft replaced propeller driven aircraft. Consequently, the demand for aviation fuel is used synonymously with the demand for jet fuel.

To date, there is no comprehensive model of the demand for jet fuel reflecting the institutional structure of the industry (O’Brien, 1981). Data problems seem prohibitive. As a result, we adopt a simple specification analogous to that used to explain the demand for diesel fuel. In particular, the aviation demand for fuel, $D_{at}$, is hypothesised to be a function of the level of economic activity (measured as per capita income), $Y$, and the price of jet fuel, $P_J$. Moreover, because of the significant increase in aviation fuel demand not reflected in these two factors, an exponential trend variable, $t$, is introduced. This yields the exact functional form:

$$\log D_{at} = \theta_0 + \theta_1 \log Y_t + \theta_2 \log P_{jt} + \theta_3 t.$$  (7)
One would expect the level of economic activity to have a positive effect on fuel demand. Moreover, as generally air line travel is a superior good, the coefficient estimate might very well exceed one. In studying the demand for air travel in the United States between 1947 and 1965, Phillips (1971) found an income elasticity of 1.45. The impact of changes in jet fuel prices on the quantity demand, if the study by the Federal Energy Administration (1976) is any indication, will be small and negative. Higher fuel prices raise the cost of air travel and thus reduce revenue passenger miles and the demand for aviation fuel.

The quantity data used in the estimation process were obtained from the Department of Energy, and the jet fuel price data from the Bureau of Labor Statistics. The information on disposable income was supplied by the Bureau of Economic Analysis. Both prices and income are in constant dollars over the period 1964 to 1978.

Table 5 reports the estimation results after the appropriate correction for serial correlation and it clearly demonstrates the importance of the level of economic activity as a determinant of aviation fuel consumption. The price elasticity likewise is significant and, as expected, relatively small. The price of jet fuel serves as a proxy for other factors. Finally, the significant time trend just reflects the movement towards increased air travel.

THE DEMAND FOR ELECTRICAL ENERGY FOR TRANSPORT

The last important energy source is electrical energy. This is used primarily for rail travel. Because it is relatively small, the causal factors influencing it have not been subjected to any consistent investigation: so an ad hoc specification is adopted, under which the demand for electrical energy in the transport sector, \( D_{eet} \), is a linear in logarithms function of the price of electrical energy to that sector, \( P_{eet} \), as well as the level of economic activity, \( Y \). This gives an exact specification of the form:

\[
\log D_{eet} = \phi_0 + \phi_1 \log Y + \phi_2 \log P_{eet}
\]

where \( \phi_0, \phi_1, \) and \( \phi_2 \) are parameters to be estimated and the other factors are as previously defined. Note that, from Table 1, in the absence of any identifiable trend, no factor representing a movement towards more intensive rail travel has been included. By analogy with the previous results, one would expect a positive coefficient on the economic activity (disposable income) variable.

The effect of a change in the price of electrical energy on the quantity demanded should be negative. Higher energy prices raise the cost of rail travel, reducing the number of revenue passenger miles, and so reducing the demand by the transport sector for electrical energy.

The quantity and price data used to estimate relationship (8) were obtained from the Edison Electric Institute, and the disposable income data from the Bureau of Economic Analysis. Both prices and income are in constant dollars over the period 1964 to 1978.

\( \text{The F.E.A. obtains a price elasticity of } -0.25. \)
TABLE 5
Aviation Fuel Demand

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Estimate$^a$</th>
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</thead>
<tbody>
<tr>
<td>$\theta_0$</td>
<td>3.9182</td>
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<tr>
<td>$\theta_1$</td>
<td>1.3619</td>
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<td>D.W.$^c$</td>
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$^a$ Standard errors of estimates in parentheses.
$^b$ Serial correlation coefficient.
$^c$ Durbin–Watson statistic.

TABLE 6
Electrical Energy Transportation Demand

<table>
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<th>Coefficient</th>
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<td>$R^2$</td>
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<td>D.W.$^c$</td>
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$^a$ Standard errors of estimates in parentheses.
$^b$ Serial correlation coefficient.
$^c$ Durbin–Watson statistic.

The estimation results are given in Table 6. (Note the required correction for serial correlation.) There are no surprises. The level of economic activity directly affects the quantity of electrical energy consumed by the sector, while price and the quantity demanded are inversely related. The fairly sizeable coefficient on the disposable income factor would suggest that electric rail travel is a superior good.
INTERFUEL SUBSTITUTION

Background

The approach used to describe interfuel substitution in the transport sector is to consider the issue as one of minimising the costs of satisfying a given level of aggregate energy demand, subject, of course, to the institutional constraints. Given this, an energy cost function, $P_E$, is hypothesised that depends on motor gasoline, diesel fuel, jet fuel, and electrical energy:

$$P_E = \Omega_E(P_m, P_d, P_j, P_{ee})$$

(9)

where $P_m$, $P_d$, $P_j$, and $P_{ee}$ denote the prices of motor gasoline, diesel fuel, jet fuel, and electrical energy, respectively. It is desirable to specify a general functional form which has a minimal number of a priori restrictions. The translog price possibility frontier allows a large degree of generality, since it places no restrictions on the Allen partial elasticities of substitution and can be viewed as a second order approximation to any arbitrary twice-differentiable price possibility frontier (Christiansen et al., 1973).

The translog price possibility frontier for the energy price aggregate is expressed as follows:

$$\log P_E = \alpha_0 + \sum_i \alpha_i \log P_i + \frac{1}{2} \sum_{i,k} \gamma_{ik} \log P_i \log P_k \quad (i, k = m, d, j, ee)$$

(10)

where the $\alpha$'s and $\gamma$'s are unknown parameters, $m, d, j, \text{ and } ee$ refer to motor gasoline, diesel fuel, jet fuel and electrical energy; $P_E$ is the price of energy, and the $P_i$'s are the prices of the energy sources. To correspond to a well-behaved cost function, a price possibility frontier must be homogeneous of degree one in prices: that is, for a fixed level aggregate energy demand, total energy expenditures must increase proportionately when all fuel prices increase proportionately. This implies the following relationships among the parameters:

$$\sum_i \alpha_i = 1$$

(11)

and

$$\sum_i \gamma_{ik} = 0 \quad (i, k = m, d, j, ee)$$

(12)

A convenient feature of the price possibility frontier approach is that the derived demand functions for the fuels can be easily computed by partially differentiating relationship (10) with respect to the energy price: that is,

$$\frac{\partial P_E}{\partial P_i} = X_i$$

(13)

This result, known as Shephard's lemma (Shephard, 1963), is conveniently expressed in logarithmic form for the translog price possibility frontier, as follows:

$$\frac{\partial \log P_E}{\partial \log P_i} = \frac{P_i X_i}{\sum_k P_k X_k} = S_i \quad (i, k = m, d, j, ee)$$

(14)
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where $S_i$ indicates the cost share of the $i$th energy source. The translog price possibility frontier yields the cost share equations as follows:

\[
S_m = \alpha_m + \gamma_{mm} \log P_m + \gamma_{md} \log P_d + \gamma_{me} \log P_e
\tag{15a}
\]

\[
S_d = \alpha_d + \gamma_{dm} \log P_m + \gamma_{dd} \log P_d + \gamma_{de} \log P_e
\tag{15b}
\]

\[
S_j = \alpha_j + \gamma_{jm} \log P_m + \gamma_{jd} \log P_d + \gamma_{je} \log P_e
\tag{15c}
\]

\[
S_{ee} = \alpha_{ee} + \gamma_{eem} \log P_m + \gamma_{eed} \log P_d + \gamma_{eee} \log P_e
\tag{15d}
\]

Note that the cost shares sum to one.

The application of Shephard's lemma implies that energy prices are exogenously determined from the transport sector. Given this, actual energy prices can be used in the estimation process without introducing the concern over simultaneous equation bias. The markets for motor gasoline, diesel fuel and jet fuel are nationwide and worldwide. The market for electrical energy is regulated. Therefore, consumption by the transport sector should have little appreciable influence on the delivered prices of the various types of energy.

Uzawa (1962) has shown that Allen (1938) partial elasticities of substitution between energy sources are given by the formula:

\[
\sigma_{ik} = (\Omega_E \cdot \Omega_E^T) / \Omega_E^T \cdot \Omega_E^i \cdot \Omega_E^k
\tag{16}
\]

where the superscripts on $\Omega_E$ indicate the partial differentiation of the cost function (10) with respect to the energy prices. For the translog price possibility frontier, one has

\[
\sigma_{ii} = \frac{\gamma_{ii} + S_i^2 - S_i}{S_i^2}
\tag{17a}
\]

\[
\sigma_{ik} = \frac{\gamma_{ik} + S_i S_k}{S_i S_k} \quad (i \neq k)
\tag{17b}
\]

for $i, k = m, d, j, ee$. Further, Allen (1938) has shown that the elasticities of substitution are related to the price elasticities of demand for energy, $\eta_{ik}$, as

\[
\eta_{ik} = S_k \sigma_{ik}
\tag{18}
\]

This formulation assumes that $\sum_k \eta_{ik} = 0$ because of linear homogeneity in energy prices.

The partial elasticities of substitution are invariant with regard to the ordering of the energy input factors. Therefore $\sigma_{ii} = \sigma_{i}$, although, in general, $\eta_{ik} \neq \eta_{ik}$.

Before we proceed, it is instructive to reflect upon just what is the objective of the estimation. The purpose here is to derive estimates of long-run possibilities of inter-fuel substitution and estimates of the price elasticities of demand. The translog formulation is a means to that end, not an end in itself.

Estimation procedure

It is feasible to estimate the parameters of the price possibility frontier using ordinary least squares. This technique is certainly attractive from the point of view of
simplicity; but neglects the additional information contained in the share equations, which are also easily estimable. Furthermore, even for a modest number of factor prices the translog price possibility frontier has a large number of regressors which do not vary much across regions. Hence multicollinearity may be a problem, resulting in imprecise parameter estimates.

An alternative estimation procedure, and the approach used here, is to estimate the cost share equations jointly as a multivariate regression system. This procedure is satisfactory, since the cost share equations include all the parameters of the price possibility frontier except the constant, and no information is lost by not including the price possibility frontier in the estimation procedure.

Additive disturbances are specified for each of the share equations. Since the cost share equations are derived by differentiation, they do not contain the disturbance term from the cost function. It is assumed that the disturbances have a joint normal distribution. Following Zellner (1962), non-zero correlations across time are allowed. Unfortunately, his proposed estimation procedure is not operational for the model described here. The estimated disturbance covariance matrix required to implement Zellner's procedure is singular, because the disturbances on the share equations must sum to zero. The Zellner procedure can be made operational by deleting one of the share equations from the system. However, the estimates so obtained will not be invariant to which equation is deleted.

Barten (1969) has shown that maximum likelihood estimates of a system of share equations with one equation deleted are invariant to which equation is dropped. Kmenta and Gilbert (1968) have shown that iteration of the Zellner estimation procedure until convergence results in maximum likelihood estimates. Iterating the Zellner procedure is a computationally efficient method for obtaining maximum likelihood estimates, and this is the procedure used here.

Data

The share equations are estimated using time series data covering the period 1964 through 1978. The data were obtained from the sources previously enumerated for the models of specific demand for energy sources.

Empirical results

The maximum likelihood estimates are invariant with regard to which equation is omitted. Consequently, equations (15a) through (15c) were estimated and the coefficient estimates of (15d) derived from these. Linear homogeneity in fuel prices constraints (i.e., relationships (11) and (12)) have been imposed. Additional regularity conditions which the price possibility frontier must satisfy in order to correspond to a well-behaved cost structure are monotonicity and convexity in energy prices. Sufficient conditions for these are positive fitted cost shares and negative definiteness of the bordered Hessian matrix of the price possibility frontier. These conditions are met at most observations for the model estimated; hence it is concluded that the estimated price possibility frontier represents a well-behaved cost structure.

Serial correlation, as with most time series models, proved to be a problem, and therefore had to be corrected for in each estimated share equation.
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One additional question arises: are the parameters on the share equations symmetric? That is, does $\gamma_{ik} = \gamma_{ki}$? To test for symmetry, which implies that an increase in the price of energy source $k$ will affect the expenditure share on energy type $i$ to the same extent as a rise in the price of energy type $i$ affects the expenditure on energy source $k$, a Quandt test is employed. The test consists of the following steps. Denote the determinants of the unrestricted and restricted estimates of the disturbance covariance matrix by $|\Sigma_u|$ and $|\Sigma_r|$ when equations (15a) through (15c) are estimated. The likelihood ratio becomes

$$\beta = \left(\frac{|\Sigma_u|}{|\Sigma_r|}\right)^{-T/2}$$

(19)

where $T$ is the number of observations. The hypothesis is tested using the fact that $-2 \log \beta$ has a chi-square distribution with degrees of freedom equal to the number of independent restrictions being imposed (Goldfield and Quandt, 1972). The test was performed with the null hypothesis being that symmetry holds. The determinant of the unconstrained covariance matrix was 178,333, while the determinant of the constrained covariance matrix was 177,942, indicating that the null hypothesis cannot be rejected at the 95% level.

Moreover, a preliminary examination of the results suggested that the serial correlation coefficient was equal across share equations. This constraint was imposed and the Quandt test employed. On the assumption that symmetry is valid, the serial correlation constrained logaritmh determinant was 177,647, suggesting that the effect of serial correlation is the same across share equations.

Following from the results of these two tests, the reported empirical estimates impose the symmetry constraint and equality of serial correlation constraint across share equations. The results are given in Table 7.

All the own-price coefficient estimates are significantly different than zero at the 95% level. The cross-price coefficients, on the other hand, are in general not so. In view of the overall inability to substitute transport modes, this is not surprising. Note that the nature of the translog function does not permit the precise testing of zero price elasticities.

Estimates of the average price elasticities of demand are given in Table 8. (Since the estimates of the elasticities of substitution tell us little, they are not reported.) Own-price elasticities should be negative and cross-price elasticities should be positive. In the significant estimates this is precisely the pattern that evolves.

There is considerable variation with regard to the energy price elasticities. The differences follow from the properties of equations (15a) through (15d) and (18) and the negative coefficients for $\gamma_{mm}$, $\gamma_{dd}$, $\gamma_{pp}$, and $\gamma_{ee}$. The transport sector is truly responding to price changes. Note, however, that the magnitude of the response is not the same in both directions. This is a reflection of methodology used in computing the price elasticities as well as of the facility with which one can switch to alternative energy sources.

What is the mechanism through which the observed interfuel substitution can be made? First, the absolute decline in the consumption of a specific type of energy is accomplished by improving the energy efficiency of the existing stock of equipment. Thus, an absolute reduction in energy consumption is realised by purchasing smaller and more efficient automobiles and discarding the less efficient.

Next, changing energy prices alter the marginal costs of operating various types
of transport equipment, and this provides an incentive to search for improvements in operating norms. Thus, reducing the average speed at which an automobile is driven (e.g., from 65 to 55 miles per hour) or altering the angle of an aircraft on take-off will result in a net reduction in the quantity of energy demanded.

Finally, as the prices of the various types of energy change relative to one another, and as this change is explicitly reflected in transport charges, there is an impetus to shift modes. Thus, as the price of motor gasoline increases relative to the price of diesel fuel, the journey to work by private automobile becomes relatively more expensive than by diesel fueled buses (that is, public transport).

In attempting to make comparisons between the interfuel elasticity estimates obtained here and those calculated elsewhere, once again a dearth of studies exists.
Table 8
Elasticities of Demand for the Transport Sector

<table>
<thead>
<tr>
<th>Elasticity</th>
<th>Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_{gm}$</td>
<td>$-0.3510^*$</td>
</tr>
<tr>
<td>$\eta_{dt}$</td>
<td>$-0.4563^*$</td>
</tr>
<tr>
<td>$\eta_{ij}$</td>
<td>$-0.1174^*$</td>
</tr>
<tr>
<td>$\eta_{mve}$</td>
<td>$-0.2494$</td>
</tr>
<tr>
<td>$\eta_{md}$</td>
<td>$0.1261^*$</td>
</tr>
<tr>
<td>$\eta_{mi}$</td>
<td>$-0.0366$</td>
</tr>
<tr>
<td>$\eta_{mve}$</td>
<td>$-0.0014$</td>
</tr>
<tr>
<td>$\eta_{dm}$</td>
<td>$0.1634^*$</td>
</tr>
<tr>
<td>$\eta_{dj}$</td>
<td>$0.0263$</td>
</tr>
<tr>
<td>$\eta_{dve}$</td>
<td>$0.0536^*$</td>
</tr>
<tr>
<td>$\eta_{jm}$</td>
<td>$0.0163$</td>
</tr>
<tr>
<td>$\eta_{jd}$</td>
<td>$-0.0154$</td>
</tr>
<tr>
<td>$\eta_{je}$</td>
<td>$0.0547$</td>
</tr>
<tr>
<td>$\eta_{em}$</td>
<td>$-0.0632$</td>
</tr>
<tr>
<td>$\eta_{ed}$</td>
<td>$0.0479^*$</td>
</tr>
<tr>
<td>$\eta_{ej}$</td>
<td>$0.0261$</td>
</tr>
</tbody>
</table>

* Significant at the 90% level or better.

One that provides estimates that are conformable is the Annual Report to Congress of the Department of Energy (1980). This study reports estimates of $-0.29$, $-0.66$ and $-0.42$ for motor gasoline, diesel fuel and jet fuel own-price elasticities. The only cross-price elasticity given is a value of $-0.37$ between motor gasoline and diesel fuel. The methodology employed is not precisely delineated, so it is difficult to conjecture why, in particular, the jet fuel own-price elasticity and the motor gasoline–diesel fuel cross-price elasticity are so divergent.

As was previously observed, a nice theoretical property of the translog formulation is that the sum of own and cross-price elasticities among energy types is zero. It is instructive to consider the magnitude of the cross-price elasticities in order to determine the main channels of inter-fuel substitution. Table 8 reports these elasticities. The effects of higher oil prices, and consequently higher diesel fuel prices, will be a stimulus to consumption of electrical energy. This will be in the form of increased rail travel as consumers shift away from trucks and buses towards trains.

TESTING FOR MODEL STABILITY

Much attention has focused on the demand for energy in the transport sector. An important question for drawing meaningful inferences over the historical period, as well as over any forecast horizon, is whether the observed relationships (i.e., price elasticities) are stable. (Stability is defined in the statistical sense of the estimated coefficients of the explanatory variables remaining constant over time.) Policy inferences are made on the basis of past behaviour. If the functional relationship
has been subject to change, then necessarily the inferences will be, at least in part, unsatisfactory.

The purpose of this section is to consider whether there is a stable demand for energy types, using a statistical test developed by Brown, Durbin and Evans (1975). This approach is adopted in preference to others available (e.g., the Chow (1960) test) because it does not require prior knowledge of the shifts. Rather it tests for the presence of such occurrences over the sample period.

To give an understanding of the test it is briefly described. A way of investigating this time-variation of a regression coefficient is to fit the regression as a short segment of \( n \) successive observations and to move this segment along the series.

A significance test for constancy based on this approach is derived from the results of regressions based on non-overlapping time segments. The method relies on a test statistic which equals the difference between the sum of squared residuals of the entire sample less the cumulative sum of squared residuals over the non-overlapping segments divided by the cumulative sum of squared residuals of the non-overlapping segments. The null hypothesis that the regression relationship is constant over time implies that the value of the test statistic is distributed as \( F \).

Specifically, consider the time segments for a moving regression of length \( n - (1, n), ((n + 1), (2n)), \ldots, ((p - 1)n + 1, T) \), where \( p \) is the integral part of \( T/n \) and the variance ratio considered (i.e., the homogeneity statistic) is

\[
\omega = \frac{(T - kp) S(1, T) - \Delta}{(kp - k) \Delta}
\]  

(20)

where \( k \) is the number of regressors, \( \Delta = (S(1, n) + (S(n + 1), 2n) + \cdots + ((pn - n + 1), T) \), and \( S(r, s) \) is the residual sum of squares from the regression calculated from observations \( t = r \) to \( s \) inclusive. This is equivalent to the usual "between groups over within groups" ratio of mean squares and under \( H_0 \) is distributed as \( F(kp - k, T - kp) \).

After this description of the test, the objective is to test explicitly for the stability of the demand for energy in the transport sector over the period 1965 through 1978. Dividing the data into two intervals of equal length (i.e., \( n = 7, p = 2 \)) allows for the computation of the test statistic for each of the share equations. As noted, one of the equations must be deleted, and as before the electrical energy equation was selected.

The tabulated value of \( \omega \), the test statistic, using equation (20) for the three share equations, is given in Table 9. The results are fairly conclusive. None of the share equations is unstable over the period 1965 through 1978.

The implications of these results for estimating the demand for energy in the transport sector are clear. Events over the past decade and a half have left virtually unchanged the demand for motor gasoline, diesel fuel, jet fuel, and (implicitly) electrical energy. That is, for the energy types used in the transport sector, the relative importance of the prices of motor gasoline, diesel fuel, jet fuel and electrical energy in influencing the shares of total expenditures (and hence demand) has remained constant.

We must be careful, however, to avoid inferring that the quantity of energy demanded has not changed. The estimation results clearly show that the prices of
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Table 9
Computed Value of the Stability Test Statistic \( \omega \)

<table>
<thead>
<tr>
<th>Share Equation</th>
<th>Computed Value of ( \omega )</th>
<th>Tabulated Critical Value*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Motor Gasoline</td>
<td>3.61</td>
<td>6.26</td>
</tr>
<tr>
<td>2. Diesel Fuel</td>
<td>3.84</td>
<td>6.26</td>
</tr>
</tbody>
</table>

* That is, \( F_{0.05} (5, 4) \).

the various energy types (in particular motor gasoline and diesel fuel and aviation fuel and electrical energy) influence expenditure shares. The magnitude of this response in the aggregate remained unaltered over the sample period. Another way of expressing this is to say that the share elasticities for the energy sources did not vary.

CONCLUSIONS

There is considerable potential for energy conservation in the transport sector in the United States. Even though substitution among energy types is limited essentially to motor gasoline and diesel fuel, there is also the potential to change between modes using alternative energy sources (Harper, 1978).

The aim in the foregoing analysis has been to examine the effect of energy prices on the quantity of energy demanded. For motor gasoline, the suggestion is that vehicle miles travelled, as well as the stock of automobiles, responds to changing motor gasoline prices. For diesel fuel consumption, aviation fuel consumption and electrical energy, the quantity of energy demanded does respond to energy prices as well as to the level of economic activity. The magnitude of the price responsiveness is typically small, since energy costs are only a comparatively small portion of the costs of truck, bus, air, and rail transport.

REFERENCES


