Measuring the Long-Run Fuel Demand of Cars

Separate Estimations of Vehicle Stock, Mean Fuel Intensity, and Mean Annual Driving Distance

Olof Johansson and Lee Schipper*

1. The Car Energy-Use Problem
Since the first so-called "oil crisis" in the early 1970s, a large number of energy demand studies have been carried out (see Dahl and Sterner, 1991a,b, or Goodwin, 1992, for surveys of petrol demand studies). In the 1970s oil imports per se were, both in the USA and Europe, perceived as a major externality, and energy prices were designed to restrain oil use; environmental problems, including the greenhouse effect, are perceived as major problems for all energy-using sectors in the 1990s (see, for example, Barker et al., 1995). As is well known, CO₂ is considered the most important greenhouse gas, and CO₂ emissions from the transport sector are approximately proportional to fossil fuel use. Since the transport sector accounts for as much as 35 per cent of fossil fuel use, emissions from this sector are obviously important. However, it is not possible to control CO₂ using catalytic converters or other available techniques. Alternatives for decreasing traffic-related CO₂ emissions are to decrease overall travel (by reducing the number of cars or the average driving distance per car), increase fuel efficiency, or change to a fuel based on renewable energy resources (or to a hydrogen or electricity system with low reliance on fossil fuels). In this study, we examine aspects of car fuel use that bear on the first two alternatives. We consider primarily long-run estimates, because of inertia in the size and characteristics of the vehicle stock.

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This paper does not consider CO₂ policies per se, but it does examine factors influencing car fuel consumption in different ways. In order to fulfil agreements on CO₂ restraint, and at the same time deal with other road traffic externalities, it is important to be able to predict how different policy instruments impact on fuel use and travel demand.

Section 2 describes the data and the variables included in the analysis. Section 3 describes the general model and some specific advantages and problems associated with pooled data. In Sections 4-6 we estimate, respectively, the size of the car stock, mean fuel intensity, and mean annual driving distance per car. Section 7 makes use of the estimated components to estimate fuel demand and travel demand, and Section 8 discusses some implications for policy.

2. Data Description and the Choice of Explanatory Variables

The data used encompass the following 12 OECD countries for the time period 1973-92: USA, UK, Japan, Australia, Germany (that is, the area known throughout most of the period of study as the Federal Republic of Germany), France, Italy, The Netherlands, Sweden, Denmark, Norway, and Finland.

These data are unique for at least two reasons. First, fuel use is disaggregated into the number of vehicles, mean fuel intensity of the car stock (that is, fuel consumption per kilometre), and mean annual driving distance per car. Information about vehicle ownership, as well as total distance driven and mean fuel intensity, have been collected and compared from various international sources by the International Energy Studies Group at the Lawrence Berkeley National Laboratory (see Schipper, Figueroa, Espey and Price, 1993; Schipper, Steiner, Figueroa and Dolan, 1993; Schipper, Steiner and Meyers, 1993; Schipper, 1995; and Scholl et al., 1996). Second, car fuel use has been differentiated between petrol, diesel, LPG, and CNG (compressed natural gas). Using "petrol" taken from national or international statistics without regard to the kinds of vehicles that use this petrol leads to serious errors in specifying the main dependent variable, errors that are neither constant over time nor the same across countries, according to Schipper, Figueroa, Espey and Price (1993). For fuel price, we have chosen the average of petrol and diesel fuel, weighted by the actual quantities of petrol and diesel fuel used by cars and personal light trucks.¹ The differences between petrol prices and the correctly weighted fuel prices are not very large for any country until the late 1980s, when significant quantities of diesel fuel were used by cars in Italy, France and Germany.

Fuel prices are taken from the International Energy Agency (1978-92) and from an unpublished survey by the US Department of Energy (1973-78). Prices have been converted to real local 1985 currency using the domestic consumer-price indices. Purchasing power parities (PPP) exchange rates from the OECD have been used to convert all different currencies to 1985 US dollars. Domestic consumer price indices, GDP, and population statistics are taken from the International Financial Statistics Yearbook, published by the International Monetary Fund (IMF).

¹ Because of data problems, we have counted LPG and CNG as petrol here. LPG and CNG consumption constitutes approximately 10 per cent of the fuel market in Italy, and less than 4 per cent in Denmark.
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It is important that analysts understand the nature of the data describing cars, their use, and their fuel consumption (Schipper, Figueroa, Espey and Price, 1993). Among the countries studied, only The Netherlands has a long-standing survey of individual car use and fuel consumption that is used by authorities to determine total fuel use by type and total distance driven. France has also undertaken surveys of both vehicle use and fuel consumption. In most other countries (Denmark, UK, Finland, Norway, USA and Germany) authorities have estimated total distance driven by a variety of techniques related to traffic counts from around the country, calibrated every few years by national travel surveys. The number of cars (by fuel type) is uncertain because of an important distinction between total registrations during the year, total registrations at any one time, and the average number of cars in use during the year, which is the figure we adopt for each country.

Measuring fuel consumption is difficult. Many countries measure petrol consumption by cars as the residual after the consumption for trucks, buses, and other vehicles is removed. This estimate is either calibrated against the few actual surveys or (more often) calibrated using estimates of fuel use per kilometre (fuel intensity) and total kilometres driven. Thus there is an inevitable circularity between fuel intensity and kilometres driven. For LPG and diesel fuel use, experts again use both surveys of car use and estimates of fuel economy to derive total fuel, and assign the large residual to heavy vehicles. There are also relatively minor border effects and adjustments for purchases made by foreign drivers in each country. Our estimates are net of these adjustments.

How serious are these problems and the errors that arise? In one sense, they are very serious, particularly as Schipper, Figueroa, Espey and Price (1993) showed how both petrol and diesel have varying shares in total car fuel over time so that rules of thumb cannot easily be used to allocate fuel. The lack of regular fuel-consumption surveys in all countries (and of any surveys at all in Italy, Sweden, and Germany) is serious, but in all but one case, a single knowledgeable authority has tried to work out all the parameters for the period of interest. The lack of any authoritative attempt to reconcile all the parameters for Sweden for the entire period studied (beyond what was done in Schipper, Figueroa, Espey and Price, 1993) is perhaps the most serious problem, but Sweden is a relatively minor country among those studied. Still, for most of the European countries, the overall changes in fuel intensity for petrol-driven cars between 1973 and 1992 are relatively small (<15 per cent), which means that uncertainties of even 5 per cent are large relative to the overall change. The errors introduced by both uncertainties and the “quasi-circular” nature of the process must be recognised, and their impacts on results borne in mind.

Furthermore, as pointed out by Dargay and Goodwin (1995), ideally one would use large-sample panel-surveys with repeated observations on the same individuals for many years (preferably also for many countries). However, in the absence of such ideal data-sets, data here are developed from the most authoritative sources and are probably the best available.

Many explanatory variables that may affect car fuel demand exist in addition to the most commonly used, petrol price and national income. Among the most important are fuel-intensity standards, taxation of new cars, taxation of car use, yearly fees for car

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ownership or inspection, or other regulations that directly affect the cost of owning and using a car (see, for example, Schipper and Eriksson, 1995). Here, based on data in Jansson and Cardebring (1989), we use a specific tax variable \( T \) to approximate other taxes related to owning a car besides fuel taxes. We define \( T \) as the sum of different kinds of purchase taxes and import fees plus the present value (on the basis of 15 years and a real interest rate of 6 per cent) of the annual tax for a specific car, a medium-sized standard car of Volkswagen Golf type. This tax variable was available for only one specific period (between 1980 and 1982). For most countries, we have more detailed information about how these kinds of taxes have changed over time, information indicating that this tax variable has been quite stable within most countries since the early 1970s. Such a variable is of course not ideal as a measure of how car ownership is taxed in different countries, since the progression with respect to important variables such as price, weight, and displacement differs between countries and may vary over time. However, in most countries, both annual and purchase taxes are roughly proportional to one of the factors measuring a car’s power or weight, as well as the car’s value. Since price, weight, and displacement are typically fairly closely correlated, the measure seems to be a reasonable approximation of the impacts through taxation (other than fuel taxation).

Geographical variables, both average population density and its distribution into urban, suburban, and rural areas, are likely to have an impact on total vehicle use. However, in the current study, data limitations force us to consider only national population density (citizens/km\(^2\)), although we know from the work of Banister and Banister (1995) that local urban density and form do affect modal choice, personal vehicle use, and total travel.

More difficult to model are variables for driver-licensing policies, road investment policies, the extent and quality of public transport systems, and cultural and political aspects. Difficult though it may be to quantify any of these variables or their impacts, it is nevertheless important to keep in mind that such variables may have a non-negligible “true” explanatory value, even if they do not appear in our regression analysis. Furthermore, omitting these variables may induce bias in the regressions. For example, if the degree of “car-friendliness” of the cultural climate is negatively correlated with the fuel price, the fuel price elasticity may be overestimated.

### 3. The Fuel Demand Model

Total demand for car fuel per capita \( Q \) is defined as the product of car stock per capita \( S \), fuel intensity (fuel consumption per kilometre driven) \( I \), and mean driving distance per car per year \( D \):

\[
Q = S \cdot I \cdot D
\]

(1)

We have chosen to model all three components separately. An obvious advantage of such a strategy is that it allows us to study how large a fraction of a long-run decrease in fuel demand, due to a fuel price increase, is the result of a decrease in the size of the vehicle.

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2 For example, it is generally more expensive to obtain a driving licence in Europe than in the USA.
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stock, a decrease in mean fuel intensity, and a decrease in mean driving distance per car. On the other hand, disaggregation is much more demanding regarding data.

It should be noted that the three components are not assumed to be independent of each other. It seems intuitively plausible that annual driving distance per car may depend both on the car stock (per capita), and on the mean fuel intensity of the car stock. For example, if a family buys a second car, total driving distance will generally increase but not be doubled; and a decrease in fuel intensity decreases variable transport cost and probably increases driving distance. However, there is no obvious reason why the vehicle stock and mean fuel intensity should be functions of each other, and/or functions of the mean driving distance, since one chooses what distance to drive for a given vehicle stock with given characteristics, and not vice versa (at least in the long run on an aggregate level). Hence, we have chosen a recursive system approach, where the mean driving distance \( D \) is estimated as a function of the car stock \( S \), the mean fuel intensity \( I \), as well as of the other variables; \( I \) and \( S \) are estimated solely as functions of other variables. This simplifies the econometrics considerably, since we need not use simultaneous equation methods.

In order to make use of our limited data set as efficiently as possible we will focus mainly on pooled cross-section time-series (CSTS) models. Without imposing any dynamic specification in the model, the simple static ordinary least-square (OLS) estimate tends to rely mainly on the “between” variation, since the “between-country” error-term is expected to have a much larger variance, as pointed out by Baltagi and Griffin (1983). Both important country-specific variables which are constant over time, as well as important variables that change over time but are constant across countries, may exist. However, it seems likely that, for variables not included in the regressions, the first category dominates. Furthermore, measurement errors are probably bigger between the countries.

One way to deal with this problem is to introduce an error-component model such as the one proposed by Fuller and Battese (1974), in which the error terms are decomposed in the CS and TS dimension as follows: \( u_{it} = v_i + e_{it} \), where \( i \) in our case represents a country and \( t \) is a year. Each error component is normally and independently distributed with constant variance, that is, \( v_i \sim N(0, \sigma_v^2) \); \( e_{it} \sim N(0, \sigma_e^2) \); \( e_{it} \sim N(0, \sigma_e^2) \) and \( E(v_i e_{it}) = E(e_{it} e_{jt}) = E(e_{it} e_{jt}) = 0 \). This implies that the error term \( u_{it} \) is homoscedastic in the time dimension and that the following conditions are satisfied: \( E(v_i v_j) = 0 \) for all \( i \neq j \); \( E(e_{it} e_{jt}) = 0 \) for all \( t \neq s \); and \( E(e_{it} e_{jt}) = E(e_{it} e_{jt}) = E(e_{it} e_{jt}) = 0 \) for all \( i \neq j \), \( t \neq s \). The correlation coefficient between \( u_{it} \) and \( u_{jt} \) \((t \neq s)\) is then independent of how far apart is time the disturbances are; see Kmenta (1986, pp. 625-6). For example, when estimating the vehicle stock, disturbance terms in the US observations are assumed to be positively correlated with each other, but the magnitude of this correlation is not assumed to be a function of the distance between the time of the observations. The variance components (the variances of the error

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3 A referee pointed out (correctly) that driving shorter distances increases fuel intensity. But it does not seem equally clear that shorter annual driving distances imply shorter trips on average. In any case, the possible overall effect on increased fuel intensity from shorter annual driving distances seems very limited.

4 Baltagi and Griffin (1983) tested several GLS estimators with different properties and, correspondingly, with large differences in estimation results.
components) are estimated by the "fitting of constant" method, and the regression parameters are then estimated by GLS; see Fuller and Battese (1974) for details.

However, fuel demand is generally found to be dynamic in nature, that is, there are time-lags between changes in the exogenous variables and changes in fuel consumption. The time-lags have several explanations, including habit persistence, slow turnover of cars in the vehicle stock, and the time required for manufacturers to change technologies in the cars they sell. A pooled static error-component model tends to bias long-run estimates downward, since in the time dimension, a static TS model typically gives lower long-run estimates than a dynamic model (see, for example, Sterner et al., 1992). In order to reflect such time-lags, one has to impose a feasible dynamic specification. In this study, we have focused on the simplest and most frequently used dynamic model, the endogenous lag model, where the endogenous variable is estimated as a function of the endogenous variable one period lagged (as well as of the exogenous variables). The main advantages of this model are that it produces immediate short-run and long-run estimates, that it is sparing with degrees of freedom, and that it often seems to produce reasonable estimates; see, for example, Franzén (1994). One of its limitations is that it implicitly assumes the adaptation process to have a geometric declining form, which of course is not necessarily correct.

It is much more difficult to specify a dynamic CSTS model correctly, compared to the pure TS case. For example, the simple OLS endogenous lag model is problematic to use (without national intercepts) since the lagged endogenous variable will be strongly positively correlated with the error term. Thus, the lagged dependent variable will be strongly biased upward, and the short-run parameter estimates will be correspondingly biased downward. However, for all fuel demand components estimated, the hypothesis that all intercepts are equal can be rejected using an $F$-test, suggesting that we should allow for different intercepts. The disadvantage of doing so is that it eliminates the pure cross-sectional explanatory information, that is, the parameter estimates will rely on the "within" variation; hence the name Within estimators. Furthermore, there will still be problems (although smaller) with positive bias in the parameter estimate of the lagged dependent variable, and the same applies to the dynamic error-component model (see Pesaran and Smith, 1995, or Baltagi, 1995, for detailed discussions on specific problems with dynamic models and pooled data). In order to take the endogeneity problem of the lagged dependent variable into account, we undertake a 2SLS estimation of the Within model. The dependent variable is then estimated simultaneously as a function of the exogenous variables and the lagged dependent variable, where the lagged dependent variable is simultaneously estimated as a function of the exogenous variables in this time period and the dependent variable two periods lagged; this may be compared with Baltagi (1995, p.110).

When using the pure CS-variation, one can avoid these dynamic specification problems by simply assuming that the parameter estimates directly reflect long-run elasticities, which implicitly assumes that each country is approximately in "equilibrium", or at least that the relative relationship between the explanatory variables for

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5 They are also frequently called fixed-effect dynamic pooled models; see Baltagi (1995).
different countries has been approximately constant for the recent past. The commonly used Between estimator is then defined as an OLS regression on the average value of each variable during the actual time period (1973-92), across countries.

Since there are important variables which are not included in the regressions, and considerable measurement errors are likely to exist, the available econometric tests for choosing the "best" estimator are clearly of limited value. Therefore, this article presents the results for several different estimators: the static OLS estimator\(^7\) (on the pooled data set without national intercepts); the traditional Between and Within estimators; a 2SLS Within estimator; GLS estimators from both a static and a dynamic error-component model; and the weighted mean of individual TS and CS parameter estimates, where the weights are inversely related to the standard error of the individual parameter estimates (see Hsiao, 1986, and Pesaran and Smith, 1995). However, for the fuel intensity estimation we rely mainly on CS-variation information, since the TS information in this case might be misleading, for reasons explained later. Although the parameters which determine fuel demand probably differ both geographically and in time, we have tried to determine representative estimations for the studied OECD countries as a whole. Alternative strategies would be almost impossible, because of data limitations.

4. Estimating the Vehicle Stock

For pragmatic reasons, we estimate all three fuel-demand components, with respect to income and fuel price, as log-linear relationships, since it is the most widely used functional form and yields constant elasticities. This makes it easy to interpret the results and compare them with other studies. According to Dahl (1986), Box-Cox tests favour the log-linear over the linear specification most often for petrol demand and distance travelled, but not for fuel intensity. There is no systematic variation detected between the linear and log-linear form. However, a log-linear relationship with respect to the taxation variable \(T\) and the population density \(G\) would be an obvious "mis-specification", since both the \(T\) and \(G\) variables contain values close to zero. A log-linear relationship implies that when the independent variable goes to zero, the dependent variable goes to infinity (if the parameter estimate is less than zero). There is of course no reason to believe that this would be a correct description of reality. Therefore, we choose instead to estimate a semi-log relationship with respect to \(T\) and \(G\), as shown in equation (2). The dynamic pooled model is then estimated as follows:

\[
\ln S_{it} = \alpha_0 + \alpha_1 \ln S_{i,t-1} + \alpha_2 \ln P_{it} + \alpha_3 \ln Y_{it} + \alpha_4 T_i + \alpha_5 G_i + u_{it} \tag{2}
\]

where the error terms \(u_{it}\) are assumed to fulfil the usual properties for each respective estimator.\(^8\) Parameters \(\alpha_2\) and \(\alpha_3\), respectively, may be interpreted as the short-run

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6 This turns out to be the case, although price differences among European countries have varied significantly over the period studied (and back to 1970, for those countries for which we have such data).
7 Although we know that this estimator is biased and inconsistent, it may be a useful and "robust" reference point.
8 There is no lagged variable in the static models. In the "Within" estimators, national intercepts are imposed. The error terms for all other estimates except the GLS and Within-2SLS are assumed to be normally distributed, with zero mean and constant variance. The same is also assumed to hold in all subsequent regressions, unless otherwise stated.
<table>
<thead>
<tr>
<th>Estimation Technique</th>
<th>Fuel Price</th>
<th>Income</th>
<th>Taxation</th>
<th>Population Density</th>
<th>Lagend</th>
<th>Adj.R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>OLS</td>
<td>–0.086</td>
<td>1.23</td>
<td>–0.060</td>
<td>–0.66</td>
<td>0.81</td>
<td></td>
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<tr>
<td>GLS₅₅</td>
<td>–0.017</td>
<td>1.17</td>
<td>–0.045</td>
<td>–0.22</td>
<td></td>
<td></td>
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<tr>
<td>Between</td>
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<td>–0.06</td>
<td>–0.63</td>
<td>0.66</td>
<td></td>
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<tr>
<td>CS-mean</td>
<td>–0.13</td>
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<td>–0.07</td>
<td>–0.66</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GLS₆₆</td>
<td>–0.020</td>
<td>0.083</td>
<td>–0.0087</td>
<td>–0.047</td>
<td>0.89</td>
<td></td>
</tr>
<tr>
<td>Within</td>
<td>–0.021</td>
<td>0.092</td>
<td>–1.8</td>
<td>–1.5</td>
<td>0.88</td>
<td></td>
</tr>
<tr>
<td>Within-2SLS</td>
<td>–0.018</td>
<td>0.26</td>
<td>4.7</td>
<td>16.1</td>
<td>0.73</td>
<td></td>
</tr>
<tr>
<td>TS-mean</td>
<td>–0.016</td>
<td>0.22</td>
<td></td>
<td></td>
<td>0.79</td>
<td></td>
</tr>
</tbody>
</table>

* OLS is a pooled Ordinary Least Square without national intercepts. GLS₅₅ and GLS₆₆ are dynamic and static error-component models. "Within" is a pooled dynamic OLS with national intercepts. "Between" is a cross-section of the average value for each country during the time period. CS-mean and TS-mean are averages from all individual CS and TS regressions, weighted with the inverse of the standard error of the individual parameter estimate. Note that the OLS, GLS₅₅, CS, and Between parameter estimates immediately reflect long-run estimates, as opposed to the others.

* Lagend is the lagged endogenous variable.

The percentage change of the vehicle stock from a one per cent increase in fuel price and national income (every other explanatory variable kept constant). Parameters α₄ and α₅, respectively, reflect the short-run percentage change of the vehicle stock with one unit increase in the taxation variable T, and the population density G. The long-run effects are simply obtained by dividing the short-run estimates by (1 – α₄) (see Johnston, 1984; W. H. Greene, 1993; or any other basic econometrics textbook).

Previous studies have shown that the vehicle stock is heavily dependent on national income, which is the result found in this study as well: the long-run income elasticity is approximately unity (see Table 1). Long-run fuel price elasticity of the car stock is rather small (about –0.1), which is also found in other studies such as Wheaton (1982).

The negative sign on the taxation-variable parameter suggests that an increase in purchase taxes or annual taxes decreases the size of the vehicle stock. A long-run parameter estimate of –0.05 would imply that the long-run decrease in vehicle stock would be approximately 0.5 per cent as a result of a USD1000 (1994 PPP) increase in the T variable, that is, an increase by USD1000 of the present value of non-fuel car taxes during
the lifetime of the car. As a result of the functional form, the (long-run) tax elasticity will be a function of the size of the tax, and hence will not be the same in all countries, but varies between 0.01 in the USA to 0.13 in Denmark.

The sign of the population-density parameter is negative, as expected. A long-run parameter value of −0.5 would imply that an increase of 10 citizens per km² is associated with a long-run decrease in the vehicle stock of 0.5 per cent. However, it is another matter to say how increases in population density would actually affect the car stock at a local or regional level. Both population density and car ownership per capita have increased over time in every country studied. If, for example, population migrated to more densely populated areas (such as, from rural areas to suburbs, or from suburbs to city centres), there might be a decline in car ownership (or use). However, the migration has often been away from dense city centres, which, together with overall increases in car ownership resulting from rising incomes, masks any effects of density on car ownership and use that might otherwise be visible at a local level in one or more countries.

Furthermore, there exist many important explanatory variables that we cannot measure at all in a simple way. The regression residuals for the Japanese observations are all negative and larger (in absolute value) than all other residuals. One would then suspect some country-specific variables for Japan, variables which affect vehicle stock negatively. By looking at the Japanese rules connected with car ownership, we find several reasons why Japan might have a smaller car stock: a garaging requirement for all cars; an expensive driver-licensing policy; a stringent and quite expensive vehicle inspection programme; and an extensive infrastructure of tolls (see Schipper and Eriksson, 1995). A dummy variable introduction for Japan (not shown in Table 1) typically gets a parameter value of about −0.35, implying that, everything else being equal, the expected size of the car stock (per capita) is about 30 per cent lower in Japan than in the other countries (since $e^{-0.35} = 0.70$). There are no other systematic parameter changes from introducing such a dummy variable, except for a minor decline in the population density parameter.

5. Estimating the Mean Fuel Intensity

The fuel-intensity component is the most difficult to estimate from pure time-series data, because of the slow and complicated adaptation process of vehicle characteristics. During the 1980s, both the fuel price and mean fuel intensity were decreasing in all countries considered, possibly indicating a positive relationship between the two, but most probably not. First, a large part of the decrease in mean fuel intensity of the car stock was due to fuel efficiency improvements in new cars during the 1970s, due in turn to a large extent to the oil crises. Second, new cars have continued to improve their fuel efficiency during the 1980s, reflecting, among other things, expectations in the early 1980s of high world oil prices in the future, and a time-lag from investments in research in fuel-efficiency measures. Such time-lags can be considerable, from a decision at company level to increase research intensity on fuel economy to an actual result in decreased fuel intensity.

However, Rouwendal (1996) recently showed that a fuel price change may affect driving behaviour, which in turn affects fuel intensity, in a non-negligible way. Hence, this price elasticity need not solely be a result of changes in car characteristics.
Table 2
Parameter Estimates for Mean Fuel Intensity of the Car Stock
(t-values in parentheses)

<table>
<thead>
<tr>
<th>Estimation Technique</th>
<th>Fuel Price</th>
<th>Income</th>
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<th>Lagend</th>
<th>Adj. R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>OLS</td>
<td>-0.38</td>
<td>-0.25</td>
<td>-0.12</td>
<td>-0.22</td>
<td>0.68</td>
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<td></td>
<td>(-15.7)</td>
<td>(-5.3)</td>
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<td></td>
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</tr>
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<td>Between</td>
<td>-0.45</td>
<td>-0.07</td>
<td>-0.10</td>
<td>-0.10</td>
<td>0.79</td>
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<td></td>
<td>(-3.9)</td>
<td>(-0.2)</td>
<td>(-2.9)</td>
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<tr>
<td>CS-mean</td>
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<td>-0.10</td>
<td>-0.14</td>
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<tr>
<td>GLSLocked</td>
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<td>-0.030</td>
<td>-0.0057</td>
<td>-0.014</td>
<td>0.95</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(-2.2)</td>
<td>(-2.9)</td>
<td>(-2.0)</td>
<td>(-0.9)</td>
<td></td>
<td>(63.7)</td>
</tr>
<tr>
<td>Within</td>
<td>-0.011</td>
<td>-0.037</td>
<td>-0.0057</td>
<td>-0.014</td>
<td>0.92</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(-1.3)</td>
<td>(-3.1)</td>
<td>(-3.1)</td>
<td>(-3.1)</td>
<td></td>
<td>(37.1)</td>
</tr>
<tr>
<td>TS-mean</td>
<td>-0.012</td>
<td>-0.074</td>
<td></td>
<td></td>
<td>0.76</td>
<td></td>
</tr>
</tbody>
</table>

in new cars. In this context, our sample of 20 years is a very short time period. In any case, our estimated dynamic relation is as follows:

\[
\ln I_{it} = \beta_0 + \beta_1 \ln I_{i,t-1} + \beta_2 \ln P_{it} + \beta_3 \ln Y_{it} + \beta_4 T_i + \beta_5 G_i + u_{it}
\]

(3)

Regression results confirm the theories above. The price elasticity from estimations based on the within-country variation is small and insignificant, and the income elasticity is typically negative (see Table 2). The latter did not change, even when a time-trend variable was included in the regressions in an attempt to incorporate various otherwise unmeasurable variables which might have influenced technological change.\(^{10}\)

The income elasticity from the regressions based on between-country variation (Between and CS-mean) are also negative (but small and insignificant). One would perhaps expect that if income had any effect upon fuel intensity, the effect should be positive due to more luxurious and heavier cars, contrary to the results here. In the Dahl (1986) survey, the average of the long-run income elasticities was 0.21, but many of the parameters were insignificant in these studies as well. On the other hand, higher national income could imply that people buy more technically-advanced and fuel-efficient cars, and that the car ownership among low-income groups increases, which could have a negative effect on fuel intensity. In the more recent survey by Dahl (1995), most studies (based on US data) indicate a negative relation, as in our results.

Since the TS-variation-based results are not reliable, for reasons discussed above, the pooled estimates will be misleading as well.\(^{11}\) Thus, we primarily rely here on the different

\(^{10}\) This fact may be a result of "spurious correlation" due to a rapid decrease in fuel intensity during a high-growth period.

\(^{11}\) The same problems seem to apply to the recent study by Espey (1996).
regressions based on CS variation. The results from the CS-mean and Between regressions indicate that long-run price elasticity is somewhat lower (absolute value about 0.4) than the long-run average value of -0.57 in Dahl (1986).

The influence of overall taxation is also shown to be significant. The result implies that a taxation increase of USD1000 (1994 PPP) during the life of a VW Golf decreases mean long-run fuel intensity by about 1 per cent (corresponding to a parameter estimate of -0.1). The sign of the population density parameter is negative, as one might have expected, since one would suspect a more dense area to support smaller and more fuel-efficient cars. However, on the other hand, one could have argued that the same cars, due to traffic conditions, would typically have a higher fuel consumption per km in a densely populated area. (Note that our data are actual fuel intensities, not test values.)

Mean fuel intensity has decreased much more rapidly in the USA than in any other country considered during the period, a change which does not correspond to any dramatic change in any of the explanatory variables. Perhaps the most important explanation is CAFE, a system of fuel-efficiency standards directed at car producers introduced in the USA in 1978. The implications of the CAFE standards are discussed in numerous articles, such as Greene (1990) and Crandall (1992). In order to make a crude test for the implications of these CAFE standards, a simple static Within regression was run, where the only explanatory variables imposed were a common time-trend variable and a country-specific time-trend variable for the USA after 1978. The parameter estimates (and t-values) were, respectively, -0.0055 (17.1) and -0.021 (-12.0), indicating that the annual mean fuel intensity decrease in the USA after 1978 has been roughly 2 per cent, in addition to the 0.5 per cent annually for the other countries. However, it may partly be the case that the uncertainty of the international oil situation has affected the US car market more than other car markets, and that this has instigated the additional intensity reductions more than the CAFE standards themselves.

Gately (1990, 1992) assumed explicitly that the part of the increased fuel efficiency (decreased fuel intensity) that is not a result of changes in comfort or performance is irreversible, because knowledge from increased research and investment remains even if fuel prices decrease again. Using this approach, he concluded that it is not necessary to include CAFE in order to explain the rapid increase of US car-stock fuel efficiency during the 1980s. It is, however, beyond the scope of this paper to judge conclusively in the somewhat heated discussion on how large a fraction of the rapid US fuel efficiency improvement was due to the CAFE standards.

6. Estimating Mean Annual Driving Distance

Of the three estimated components, mean annual distance driven per car is, in a sense, the most difficult, because of the large number of possible explanatory variables. There are at least seven possible explanatory variables and only 12 countries in our CS analysis. The estimation process is made more difficult because some of the potential explanatory variables are closely correlated. Significance levels are therefore rather poor; hence, the parameter estimates should be treated with great care. The dynamic models were estimated as follows:
Table 3
Parameter Estimates for Mean Annual Driving Distance
(t-values in parentheses)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>OLS</td>
<td>-0.33</td>
<td>-0.073</td>
<td>0.066</td>
<td>0.13</td>
<td>-0.20</td>
<td></td>
<td>0.62</td>
</tr>
<tr>
<td></td>
<td>(-9.3)</td>
<td>(-0.9)</td>
<td>(6.2)</td>
<td>(2.3)</td>
<td>(-3.1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GLS_{Stat}</td>
<td>-0.13</td>
<td>0.31</td>
<td>0.044</td>
<td>-0.25</td>
<td>-0.79</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(-6.3)</td>
<td>(5.0)</td>
<td>(1.0)</td>
<td>(-5.7)</td>
<td>(-3.4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Between</td>
<td>-0.47</td>
<td>0.26</td>
<td>0.066</td>
<td>0.05</td>
<td>-0.12</td>
<td></td>
<td>0.56</td>
</tr>
<tr>
<td></td>
<td>(-1.6)</td>
<td>(0.4)</td>
<td>(0.9)</td>
<td>(0.1)</td>
<td>(-0.4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CS-mean</td>
<td>-0.41</td>
<td>0.33</td>
<td>0.066</td>
<td>-0.044</td>
<td>-0.26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GLS_{Dyn}</td>
<td>-0.061</td>
<td>0.005</td>
<td>0.002</td>
<td>-0.006</td>
<td>-0.039</td>
<td>0.89</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(-4.9)</td>
<td>(0.1)</td>
<td>(0.4)</td>
<td>(-0.3)</td>
<td>(-1.2)</td>
<td>(36.4)</td>
<td></td>
</tr>
<tr>
<td>Within</td>
<td>-0.066</td>
<td>0.041</td>
<td>-0.018</td>
<td>0.70</td>
<td></td>
<td>0.98</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(-5.6)</td>
<td>(1.0)</td>
<td>(-0.5)</td>
<td>(17.1)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Within-2SLS</td>
<td>-0.12</td>
<td>0.17</td>
<td>-0.16</td>
<td>-0.32</td>
<td></td>
<td>0.98</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(-6.5)</td>
<td>(2.5)</td>
<td>(-3.1)</td>
<td>(2.1)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TS-mean</td>
<td>-0.11</td>
<td>0.091</td>
<td>0.00005</td>
<td>0.36</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ \ln D_{it} = \gamma_0 + \gamma_1 \ln D_{it-1} + \gamma_2 \ln(P_{it}) + \gamma_3 \ln(I_{it}) + \gamma_4 T_i + \gamma_5 G_i + \gamma_6 \ln S_{it} + u_{it} \]  

where \((P/I)\) is the product of the fuel price and the mean fuel intensity, that is, it is the mean fuel cost per kilometre. Thus, in order to save degrees of freedom, we have implicitly assumed that the fuel-price elasticity is equal to the fuel-intensity elasticity.\(^2\) From US TS data, D. L. Greene (1993) has measured this "rebound effect" or the \(D\)-elasticity with respect to the variable fuel-cost, to be about \(-0.13\) in the USA (in both the short and long run), which is lower than most of our estimates.

As shown in Table 3, the dynamic GLS and Within models gave unrealistically high parameter values of the lagged variables, which one could expect according to Pesaran and Smith (1995), whereas the TS-mean and Within-2SLS gave considerably more reasonable estimates in this respect. Income elasticities are generally positive (although insignificant in some regressions), but vary considerably. The negative OLS-estimate can best be explained by the strong co-linear relation between income and the car stock.

The taxation parameter tends to be positive (but the estimates are often insignificant), that is, an increased car-purchase or annual tax implies a higher mean driving distance per car, which seems reasonable. Estimated influences of the size of the car stock are often

\(^2\) Although this common formulation may seem reasonable, it is not axiomatic correct, because other characteristics might change with fuel intensity, such as driving comfort, which may be correlated with fuel intensity as well as with mean annual driving distance.
small and insignificant, but mostly negative, as expected. The influence of population density seems negative.

As for the other components, there exist several important explanatory variables which we could not measure appropriately. One such is the various taxation rules in relation to so-called “company cars”, that is, cars provided by employers to employees in lieu of reimbursement of expenses. Company car schemes may involve leasing or other arrangements and are usually lightly taxed, often with a zero marginal tax (see Schipper, Steiner, Figueroa and Dolan, 1993). Company cars are particularly common in the UK, which in our regressions is reflected in large positive error terms for the UK observations (when CS variation is used).

7. Long-Run Fuel Demand and Travel Demand

The estimated elasticities (and other parameters) for the three components of fuel demand are in principal additive, although the fact that $S$ and $I$ appear as explanatory variables in the $D$ equation has to be considered. Writing the identity (1) in log-form, we can identify the estimated parameters in equations (2), (3), and (4) to obtain a reduced form for the long-run fuel demand (for the dynamic models, ignoring intercepts and error terms): \[ \ln Q = \ln S + \ln I + \ln D \]

\[
\begin{align*}
\ln P & = \left[ \frac{\alpha_2}{1 - \alpha_1} \left( 1 + \frac{\gamma_6}{1 - \gamma_l} \right) + \frac{\beta_2}{1 - \beta_1} \left( 1 + \frac{\gamma_2}{1 - \gamma_l} \right) + \frac{\gamma_5}{1 - \gamma_l} \right] \ln P \\
\ln Y & = \left[ \frac{\alpha_3}{1 - \alpha_1} \left( 1 + \frac{\gamma_6}{1 - \gamma_l} \right) + \frac{\beta_3}{1 - \beta_1} \left( 1 + \frac{\gamma_2}{1 - \gamma_l} \right) + \frac{\gamma_3}{1 - \gamma_l} \right] \ln Y \\
T & = \left[ \frac{\alpha_4}{1 - \alpha_1} \left( 1 + \frac{\gamma_6}{1 - \gamma_l} \right) + \frac{\beta_4}{1 - \beta_1} \left( 1 + \frac{\gamma_2}{1 - \gamma_l} \right) + \frac{\gamma_4}{1 - \gamma_l} \right] T \\
G & = \left[ \frac{\alpha_5}{1 - \alpha_1} \left( 1 + \frac{\gamma_6}{1 - \gamma_l} \right) + \frac{\beta_5}{1 - \beta_1} \left( 1 + \frac{\gamma_2}{1 - \gamma_l} \right) + \frac{\gamma_5}{1 - \gamma_l} \right] G
\end{align*}
\]

The factors in square brackets are then, respectively: the calculated long-run fuel-price elasticity; the long-run income elasticity; the long-run taxation parameter; and the long-run population-density parameter.

The sum of the $S$ and $D$ parameters can be interpreted as the parameter estimates for the long-run travel demand. Table 4 shows the approximate range of long-run estimates for $S$ and $D$, obtained by using all the regressions, but for fuel intensity $I$ we show only those which rely primarily on between-country information (for reasons discussed earlier).

We find a long-run fuel-price elasticity of about –0.7, in which the largest fraction is due to changes in cars’ fuel intensity, and we find a long-run income elasticity of about 1.2, almost all due to the size of the car stock, that is, the number of cars. The total figures are close to the “core” values from other studies which used non-disaggregated models (see Franzén and Sterner, 1995; the surveys by Dahl and Sterner, 1991a,b; and Goodwin, 1992).
Table 4
Approximate Range of the Estimated Long-Run Parameters from Regressions, Including Indirect Effects
["best guess" in brackets]a

<table>
<thead>
<tr>
<th>Estimated Component</th>
<th>Fuel Price</th>
<th>Income</th>
<th>Taxation (other than fuel)</th>
<th>Population Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car stock</td>
<td>-0.20 to 0.0</td>
<td>0.75 to 1.25</td>
<td>-0.08 to -0.04</td>
<td>-0.7 to -0.2</td>
</tr>
<tr>
<td></td>
<td>[-0.1]</td>
<td>[1.0]</td>
<td>[-0.06]</td>
<td>[-0.4]</td>
</tr>
<tr>
<td>Mean fuel intensity</td>
<td>-0.45 to -0.35</td>
<td>-0.6 to 0.0</td>
<td>-0.12 to -0.10</td>
<td>-0.3 to -0.1</td>
</tr>
<tr>
<td></td>
<td>[-0.4]</td>
<td>[0.0]</td>
<td>[-0.11]</td>
<td>[-0.2]</td>
</tr>
<tr>
<td>Mean driving distance (per car per year)</td>
<td>-0.35 to -0.05</td>
<td>-0.1 to 0.35</td>
<td>0.04 to 0.12</td>
<td>-0.75 to 0.0</td>
</tr>
<tr>
<td></td>
<td>[-0.2]</td>
<td>[0.2]</td>
<td>[0.06]</td>
<td>[-0.4]</td>
</tr>
<tr>
<td>Car fuel demand</td>
<td>-1.0 to -0.40</td>
<td>0.05 to 1.6</td>
<td>-0.16 to -0.02</td>
<td>-1.75 to -0.3</td>
</tr>
<tr>
<td></td>
<td>[-0.7]</td>
<td>[1.2]</td>
<td>[-0.11]</td>
<td>[-1.0]</td>
</tr>
<tr>
<td>Car travel demand</td>
<td>-0.55 to -0.05</td>
<td>0.65 to 1.25</td>
<td>-0.04 to 0.08</td>
<td>-1.45 to -0.2</td>
</tr>
<tr>
<td></td>
<td>[-0.3]</td>
<td>[1.2]</td>
<td>[0.0]</td>
<td>[-0.8]</td>
</tr>
</tbody>
</table>

a What the present authors consider as most reasonable, on the basis of regressions, knowledge of data limitations and statistical methods, and experiences.

The survey by Dahl (1986) presents results for a disaggregated model similar to ours, but with only two components, fuel intensity and total distance driven per time period. In that study, the long-run price elasticity of fuel demand is -1.12, of which the two components have roughly the same magnitude, and the long-run income elasticity is 0.81, of which the major part (0.6) comes from total distance driven (S times D, with our notations). According to our study, fuel demand is price-inelastic but income-elastic, while the results from Dahl are the other way round. Furthermore, our long-run travel-demand price elasticity is not far from the recent surveys by Oum et al. (1992) and Goodwin (1992), which both found elasticities near -0.3. Neither of them presented any income elasticities.

The taxation variable works both through the vehicle stock and through fuel intensity, with a counteractive effect through the mean annual driving distance per car. A total long-run taxation parameter of -0.11 suggests that total long-run fuel consumption would decrease by about 1.1 per cent as a result of an increased (non-fuel) tax on car ownership (and use) of USD1000 (1994PPP). As a comparison, for the same fuel-intensity reduction with a fuel tax ($\epsilon_p = -0.7$), a fuel price increase of 1.6 per cent is needed. Assuming the fuel intensity of a 1981 VW Golf to be 0.08 litre/km, and its driving distance to be 15,000 km/year for 15 years, the real fuel price to be USD0.75/litre (the mean value for all countries and years considered), and a real discount rate of 6 per cent, yields a total present value of the fuel-tax increase of USD140 (1994PPP), which is considerably less than USD1000. Although the assumptions are quite rough, the conclusion seems clear: per amount of tax paid, a fuel tax affects fuel use far more than a combination of car-purchase
and annual taxes do. The result is hardly surprising, since a fuel tax affects fuel consumption more directly. However, it should be noted that we have not considered specific "gas-guzzler" taxes or any other taxes designed primarily to reduce fuel intensity. Such taxes would probably influence fuel intensity much more than our T-variable does.

The overall estimated population-density parameter is negative in all estimated fuel-demand components, with an overall long-run parameter of about −1, corresponding to an overall fuel consumption decrease of about 1 per cent, resulting from an increased population density of 10 citizens/km². Thus, population density seems to affect fuel demand in a non-negligible way.

8. Implications for Policy

Traditional economic wisdom claims that one should tax negative externalities as directly as possible, in order to minimise overall disturbance losses to society. For externalities related primarily to fuel use, such as the greenhouse effect, it is thus generally assumed to be better to tax fuel directly, rather than, for instance, to tax car ownership. This seems confirmed by our results since, per total amount of tax paid, a fuel tax increase would reduce overall long-run fuel consumption much more than an increase in the other car-related taxes.

However, some important externalities, such as congestion and noise, are functions of total distance driven rather than of total fuel consumed. A tax on fuel use here would cause people to adjust their behaviour in the long run, primarily through their choice of cars, so that total distance driven would be affected much less than fuel use. From a social point of view, it would therefore be much better if it were possible to tax the distance driven directly, instead of indirectly through fuel use. Furthermore, since these external costs, and local pollution costs, differ strongly in time and space, an introduction of an advanced road-pricing system, where the charges could be differentiated in time, space, and with respect to important vehicle characteristics, may be something to promote in the future.

References


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