## DIMENSIONS OF AUTOMOBILE DEMAND. A METHODOLOGICAL OVERVIEW OF A RESEARCH PROJECT

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ABSTRACT: The major objective of the study on the dimensions of automobile demand (1981-1988) is to obtain reliable forecasts of the variables which drive the fundamental energy equation: energy consumed (litres) = efficiency of technology (litres/100 kilometres) \* utilisation rate (kilometres per period). Since the level of utilisation is unlikely to be independent of the state of technology, and both dimensions are conditioned by the state of the economy and the nature of households as well as the extent of corporate sector support to the household sector, it is necessary to view the levels of vehicle usage and vehicle fuel efficiency as outputs of the broader household decision process. This broader context can be represented by a study of the household's choice of automobiles (by number and composition) and levels of utilisation. This perspective enables us to view vehicle efficiency and utilisation as derivatives of a study of the household's demand for mobility services which are derived from the demand for end activities (consumption of goods and leisure). Since we are especially interested in the role of fuel prices and vehicle technology in the household's decision on the level of vehicle utilisation, it is desirable to monitor the response path of a sample of households over a period of time. A single cross-section approach cannot identify the influence of changing fuel prices on vehicle use, nor adequately accommodate the temporal relationship between vehicle purchase/disposal decisions and the utilisation rate. To satisfactorily represent the role of policy variables (e.g. fuel prices, taxes associated with vehicle possession, standards for vehicle technology) in the context of the wider set of influences on household automobile possession and usage, we have developed an econometric model system which jointly models the household's choice of vehicles and utilisation level over the period 1981-1985. This paper provides a methodological overview of the project which in its entirety is due for completion in late 1988.

#### INTRODUCTION AND OBJECTIVES

The 'energy crises' of the 70's have provided us with a rich experience of the ways in which various sectors of society adjust their patterns of behaviour in response to non-marginal changes in the price of essential resources. Some groups are able to change their consumption/ production profile without penalty, while others incur significant costs. Although knowledge gained during an event is invaluable in future planning, the ability to predict the possible consequences of future actions is also desirable, especially where there are early warning signals. This capability was not available in relation to the events in the 70's; if we are to benefit from the experiences of the past it is necessary to establish formal methods to evaluate the implications on energy consumption of changes which leading indicators suggest have a high probability of occurrence (e.g. ageing of the population, continual increases in fuel prices, improvements in the weight and fuel efficiency of vehicles, and increases in leisure time). The extent of this change is critical in the calculation of levels of energy consumption.

The primary objective of the dimensions of automobile demand study (henceforth 'auto project') is to develop an empirically-based econometric modelling system with the capability of determining levels of vehicle utilisation and fuel efficiency, the critical variables in the fundamental energy consumption formula. The study is specialised to the household sector (of urban Australia), a significant consumer of petroleum, estimated as 1.9 billion litres in 1981 for the Sydney Metropolitan Area (Hensher et al., 1985).

Households do not derive utility from fuel efficiency and vehicle use per se; these are inputs in a complicated equation of the household decision-making process, where the influence of corporate sector supports, household activity needs, financial circumstances, costs of vehicle possession and use, and preferences for particular types of vehicles all interact to determine the level of use and vehicle efficiency. Since the level of use and vehicle fuel efficiency (embodied in vehicle type) are unlikely to be independent contributions to the energy equation, it is essential to model jointly the household's decisions on vehicle purchases and vehicle usage. The strict relationship between the two decisions can only be identified using household-level data. Such data can also account for the relationship between vehicles in multi-vehicle households, which we have identified as having a strong influence on levels of vehicle-specific use (Hensher 1984, 1985a). Since the relationship between changes in influences on use and vehicle efficiency are not temporally instantaneous, it is necessary to introduce an intertemporal specification. To accommodate this with household level data necessitates the development of a panel data base. Reliance on a single cross-section, which cannot account for the role of varying fuel prices, and which uses strong transferability assumptions on household behaviour as a particular household changes its 'position' in the sample (e.g. moves from medium to high income) provides insufficient statistical leverage to separate the effects of persistent interindividual differences from real

intertemporal relationships. A panel is required to sort out the 'causal' patterns (Hensher and Wrigley 1986, Hensher 1986a).

The overall framework of the study is summarised in Figure 1. There are three major modules - a vehicle choice (discrete choice) module, the atemporal intra-household vehicle use module and the intertemporal vehicle use module. The discrete-choices are a nested set of three decisions on choice of vehicle type mix, body mix and quantity, estimated as holdings in Waves 1 to 4. They are pooled in the dynamic specification to obtain final parameter estimates for linking the vehicle choice and use modules. We assume contemporaneous dependency among vehicle use levels in multiplevehicle households, with vehicle v's use in period t only influencing the level of use of another household vehicle v<sup>-</sup>, in period t+1 via v's influence on v<sup>-1</sup>'s utilisation level in period t. The contemporaneous dependency is allowed for in the intertemporal (vehicle-specific) usage model via a predetermined parameterised intra-household vehicle use substitution variable (v in Figure 1).

This paper is organised as follows: the next section sets out the underlying economic theory for the static and dynamic specifications, which is followed by a summary of the econometric system used in intraand inter-temporal modelling. The panel data is then described as well as other data sources. We then discuss the policy relevance of the study. The concluding section emphasises the overall contribution of the study. We draw on papers of the project which contain details on the derivation of model forms etc.





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The Overall Framework of the Model System

#### THE THEORETICAL FRAMEWORK

We begin with a static representation of individual (household) choice behaviour, and once the essential elements are identified for the myopic case it is relatively simple to introduce a temporal (or dynamic) dimension. We assume that individuals as consumers behave as if they are utility maximisers, and that the choice of vehicle technology (i.e. choice of a consumer durable) and its level of utilisation are in theory determined simultaneously as the solution to a single utility maximisation problem. A household is faced with a universal (but finite) set of mutually exclusive vehicles and selects one alternative out of the set of discrete alternatives in conjunction with the choice of level of vehicle utilisation. That is, the household makes a discrete choice and a continuous choice.

The Static (Atemporal) Approach

Formally, the (direct) utility function is defined as

$$u[x,b,z] \equiv u[x,\psi_{1}(b_{1}),\psi_{2}(b_{2}),\dots,\psi_{j}(b_{j}),z] \qquad (1$$

where x is the level of vehicle utilisation,  $\psi_i(...)$  is an index function of the quality of the i<sup>th</sup> vehicle, with  $b_i$  a vector of the set of attributes (1, ..., K) associated with a unit of use of vehicle i (i.e.  $b_i = [b_{11}, b_{12}, ..., b_{1K}]$ ) such as fuel efficiency, luggage capacity, interior space dimensions, boot depth, and acceleration. z is the standard Hicksian composite commodity used as the numeraire.

The x and z vectors relate to the utilisation decision, and  $\psi_i(b_i)$  relate to the choice of vehicle. If (1) is defined for all levels of utilisation and all vehicles it is an unconditional direct utility function and is maximised subject to an unconditional budget constraint (with  $p_i$  the unit price of consumption of the i<sup>th</sup> alternative, which is the cost per kilometre of vehicle use and  $r_i^c$  the expected annualised capital cost of vehicle i):

$$\sum_{i \in J} [p_i \times_i + r_i^c] + z = Y$$
(2)

and the usual non-negativity constraints of  $x_i \ge 0$ ,  $z \ge 0$  and  $x_i x_j = 0$ . Y is total income. It is appropriate to redefine the direct utility function to recognise that the level of vehicle use is conditional on the vehicle chosen. The conditional direct utility function can be defined as

$$\overline{u}_i \equiv \overline{u}_i \quad [x_i, \psi_i, z]$$

(3)

Maximisation of (3) subject to a conditional budget constraint,  $p_i x_i + r_i^c + z = Y$  and the condition that the shape of the underlying preferences does not include zero level of use of vehicle i (i.e.  $x_i > 0$ ), yields a conditional demand function  $\overline{x_i}(p_i, \psi_i, Y-r_i)$ , the vehicle usage function.  $r_i$  is the total annualised life cycle cost, equal to  $p_i x_i + r_i^c$ . The attributes of the i<sup>th</sup> vehicle are endogenous influences on the level of vehicle use, and that although these attributes enter directly into the discrete-choice model and not the vehicle. Failure to recognise and account for this endogeneity in the usage equation results in selectivity bias. The many previous studies on levels of consumption which failed to include the choice of consumer durable associated with the consumption are contenders for selectivity bias. Only in the rare circumstance of independence is there no problem.

The demand function for vehicle use is concerned with an individual confronted with a given set of prices and income, who wants to choose an optimal bundle (i.e. levels of vehicle use and z) from the feasible set defined by the maximum utility level of vehicle use emanating from maximisation of the conditional direct utility function subject to constraints. We need however to explicitly represent the discrete choice problem so that its econometric link with the vehicle use model flows from the joint maximisation problem. Given the predetermined maximum utility level of vehicle use (the optimal bundle) we can ask what set of prices, quality and income will make the individual choose that particular level of use and level of z? The optimal level of  $x_t$  and z is associated with a specific vehicle and is thus a conditional optimum. The 'global' optimum is associated with the vehicle in the choice set which yields the maximum level of (indirect) utility. Different prices, (qualities) and income produce different maximum utility levels of demand. That is, each discrete alternative is associated with a different optimal bundle of x and z (because we condition the direct utility function on the selected alternative). Thus the conditional indirect utility function associated with the choice of vehicle is defined as

 $v[p, \psi, Y] = \max[\overline{v}_1(p_1, \psi_1, Y-r_1), \overline{v}_2(p_2, \psi_2, Y-r_2), \dots,$ 

$$\overline{v}_{1}(p_{1}, \psi_{1}, Y-r_{1})]$$
 (4)

The discrete choice rule, given that the preferences of the deterministic utility maximising individual are incompletely observed is

$$\pi_{i} = \operatorname{Prob}[\overline{v}_{i}(p_{i}, \psi_{1}, Y-r_{1}) \geq \overline{v}_{j}(p_{j}, \psi_{j}, Y-r_{j}) \forall i \in J, i \neq j].$$
(4a)

The conditional (ordinary) demand equation can be derived using Roy's identity,  $\overline{x_i}(.) = \frac{\frac{\partial V}{\partial p_i}}{\frac{\partial V}{\partial Y}}$ . A number of functional forms for

an indirect utility function have been investigated in the econometric literature; however very few are both computationally tractable and capable of handling fixed costs. Hanemann's recent contribution (Hanemann 1984) yields tractable forms but implicitly assumes the absence of any annualised capital costs. Dubin and McFadden (1984) propose a specification based on Hausman's (1981) derivation of an indirect utility function from a demand equation which is linear in income and prices. The indirect utility function proposed by Dubin and McFadden (1984) and suitably modified is:

$$\overline{V}_{i}(\cdot) = \gamma([W_{i}(p_{i}) + \psi_{i} + Y - r_{i} + v_{i}/\beta_{i}]e^{-D_{i}p_{i}})$$
(5)

where

$$W_{i}(p_{i}) = \int_{p_{i}}^{0} m_{i}(t) e^{\beta_{i}(p_{i}-t)} dt$$
(5a)

Y is a general functional form,

 $\beta_i$  is an unknown parameter,

 $\nu_{\vec{i}}$  is the unobserved component which depends in general on the choice of vehicle i.

and  $p_i$  the unit price of vehicle use (which varies across vehicles). Given (4a),  $\overline{y_i}$ 

$$\frac{\partial \mathbf{V}_{i}}{\partial \mathbf{p}_{i}} = \frac{\partial \mathbf{Y}}{\partial z} \left( -\left[\mathbf{W}_{i} \left(\mathbf{p}_{i}\right) + \mathbf{Y} - \mathbf{r}_{j} + \mathbf{v}_{i}/\beta_{i}\right]\beta_{i} + \left[\frac{\partial \mathbf{W}_{i}}{\partial \mathbf{p}_{i}}\right]e^{-\beta_{i}P_{i}}\right)$$

$$ere \quad z = \left[\mathbf{W}_{i} \left(\mathbf{p}_{i}\right) + \psi_{i} + \mathbf{Y} - \mathbf{r}_{i} + \mathbf{v}_{i}/\beta_{i}\right]e^{-\beta_{i}P_{i}}$$

$$(6)$$

$$\frac{\partial W_{i}}{\partial p_{i}} = \int_{p_{i}}^{o} \beta_{i} (m_{i}(t)e^{\beta_{i}(p_{i}-t)}) dt - m_{i}(p_{i})$$

$$= \beta_{i} W_{i}(p_{i}) - m_{i}(p_{i})$$
Thus
$$\frac{\partial V_{i}}{\partial p_{i}} = -\frac{\partial Y}{\partial z} \left[ (Y - r_{i})\beta_{i} + \Psi_{i} + m_{i}(p_{i}) + V_{i} \right] e^{-\beta_{i}p_{i}}$$

$$\frac{\partial \overline{V}_{i}}{\partial Y} = \frac{\partial Y}{\partial z} e^{-\beta_{i}p_{i}}$$
Thus
$$\overline{x_{i}} = \frac{\partial V/\partial p_{i}}{\partial V/\partial Y} = \beta_{i}(Y - r_{i}) + m_{i}(p_{i}) + V_{i}$$
(7)

The resulting conditional demand equation (for vehicle use) (7) is linear in parameters and readily estimable using standard econometric methods. For multiple-vehicle households there will be as many equation (7)'s as there are vehicles. Three stage least squares is then the appropriate method (see below). The conditional indirect utility function (5) is nonlinear in the parameters and requires non-standard computational software.

It should be noted that the probability density of  $x_i$ ,  $f_{x_i}(x)$  is not independent of the choice of vehicle technology (as defined by

(4a) and (5)). For computational convenience we set  $v_i = n$ , a random effect independent of alternative i, and introduce  $\varepsilon_i$  as an alternative specific random effect when we specify the estimable form of (5). Since we can specify the right hand side of (5) as

 $\overline{V}_{i}(.) = (\alpha_{0i} + \sum_{k}^{\Sigma} \theta_{k} b_{ik} + \alpha_{1} p_{i} + \beta_{i} (Y - r_{i}) + \eta) e^{-\beta_{i} p_{i}} + \varepsilon_{i} \qquad (8)$ where  $\alpha_{0i} + \sum_{k}^{\Sigma} \theta_{k} b_{ki} = \psi_{i}$ .

The interdependence between choice of vehicle and level of use is defined as  $\left( \begin{array}{cc} \pi_{i} & f_{x_{i}} | \epsilon \epsilon A_{i} \end{array} \right)$  for x > 0

$$f_{x_{\tilde{f}}}(x) = \begin{cases} 1 - \pi_{\tilde{f}} & \text{for } x = 0 \end{cases}$$
(9)

where  $f_{x_i} \in CA_i$  (x) is the probability density of  $\overline{x_i}$ , the level of demand (usage) associated with the chosen vehicle; A<sub>i</sub> is the feasible choice set containing i.

The likelihood function for the sample of individuals drawn from a closed population is, for x > 0:

$$\zeta = \prod_{q=1}^{Q} [\pi_{cq} f_{x_{cq}} | \epsilon \epsilon A_{q} (x_{cq})]$$
(10)

where c is the chosen alternative in the set A. A two-stage estimation procedure is used, given the complexity of the joint likelihood function. The discrete-choice is estimated initially, then a suitable linking index is calculated to account for the presence of self-selectivity which occurs if an individual choosing particular vehicles uses them more than or less than observationally identical individuals drawn randomly from the sampled population. Selectivity correction involves recognition of the potential correlation between the unobserved components of the discrete and continuous choices and the determination of a method of handling the endogeneity of the unobserved attributes of the vehicle in the utilisation model. Selectivity correction formulae can take many forms according to the functional relationship between the discrete and continuous choices. If we assume that the cumulative distribution function of the error terms in the discrete-choice model is IID extreme value type i (equation 11)

 $F_e(\varepsilon_1, \ldots, \varepsilon_j) = \exp \left[-\Sigma \exp(-\varepsilon_i/\mu)\right]$  with scale parameter  $\mu > 0$  (11)

then it can be shown (see Dubin and McFadden 1984) that the mean of the unobserved influences on the discrete choice that are not independent of the unobserved influences on the continuous choice is given as equation 12.

$$E(n|\delta_{i}=1) = -\frac{6}{\pi^{2}}\rho_{i}\sigma \left[ \text{Log Prob}_{i} + \sum_{\substack{j=1\\j\neq i}}^{J} \text{Log Prob}_{j} \left( \frac{Prob_{j}}{1 - Prob_{j}} \right) \right]$$
(12)

Prob. is the predicted probability of an individual selecting alternative j from the set of discrete alternative vehicles. The coefficient of this 'selectivity correction' variable is  $-\frac{6}{\pi^2}\rho_i\sigma$ , where  $\sigma$  is the standard error of the selectivity parameter and  $^{\pi^2}\rho_i$  can be derived. Further details on selectivity correction are given in Hensher and Milthorpe (1985) and Dubin and McFadden (1984).

The empirical forms of the conditional indirect utility equation associated with choice of vehicle type, and the conditional (ordinary) demand equation for vehicle utilisation are given in (13) and (14).

$$\overline{\mathbf{V}}_{i} = \begin{bmatrix} \frac{\alpha_{0i}}{\mu} + \sum_{k=1}^{K} \frac{\partial ki}{\mu} \mathbf{b}_{ki} - \alpha_{1i}\mathbf{p}_{i} - \frac{B_{1}}{\mu}\mathbf{F}_{i} - \frac{B_{1}}{\mu}\mathbf{V}_{i} - \frac{B_{1}}{\mu}\mathbf{V}_{0}\mathbf{C}_{1} - \frac{B_{1}}{\mu}\mathbf{V}_{1}\mathbf{V}_{1} \end{bmatrix} e^{-\frac{B_{1}}{\mu}\mathbf{F}_{i}} + \varepsilon_{i}$$

$$(13)$$

$$\overline{\mathbf{x}}_{i} = \alpha_{0i} + \sum_{n=1}^{N} \phi_{ni}\mathbf{z}_{ni} + \alpha_{1}\mathbf{p}_{1} + \frac{B[Y^{n}(\mathbf{T}\mathbf{C}_{i} + \mathbf{H}_{i} + \mathbf{F}_{i}]) - (13)}{\sum_{n=1}^{M} (13)} = \left[ \frac{\frac{B_{1}}{\mu}\mathbf{v}_{i}}{\mu} \right] \left[ Log \ Prob_{i} + \sum_{j=1}^{L} Log \ Prob_{j} \left( \frac{Prob_{j}}{1 - Prob_{j}} \right) \right] + \varepsilon_{i}$$

$$(14)$$

where the new notation defines:

 $p_{1}^{2}$  = unit price of vehicle use (defired as petrol cost only in c/km)

c = capital cost of vehicle (measured by new or used price)

= gross household income

ti ≠ annual maintenance and repair Costs

F. = annual fuel cost

N.+F. = 2,X.

τ = an unknown discount rate as a function of household income:

 $\tau = \tau_0^+ \tau_1^- Y$  to obtain unsualised capital cost of a vahicle

 $z_{\rm pi}$  " a vector of other explanatory variables influencing vehicle

utilisation

€(c<sub>7</sub>n) ≠ 0

θ φ α β are parameters

 $\xi_1$  is the disturbance term associated with vehicle use which is independent of vehicle choice (E( $\xi_2$ ,) = 0)

All unknowns in a logit specification of the discrete choice model are scaled by a non-negative parameter  $\mu$ . Other differences between (8) and (13) follow from the empirical assumption that the unknown discount rate ( $\tau$ ) for the annualised cost of capital is assumed to be a function

of income. Given  $r_i = p_i x_i + r_i^c$ ,  $r_i^c = \tau C$ , substitution into (8) gives (13), after  $\beta_i^{\gamma}$  cancels out since Y does not vary across the vehicle choice.

Intertemporal (Dynamic) Extensions

Intertemporal utility maximisation is best viewed as an extension of the myopic model of individual choice behaviour with the elements of the static structure forming the building blocks for a multiperiod model of consumer behaviour. We assume that decisions are made at discrete intervals and that behaviour (embodied in plans) is revisable after every period (although revisions do not have to occur). Thus as an individual moves through time and arrives at later points of time within the horizon of a plan, non-fulfilment of expectations may necessitate a revision in the plan for the remaining periods of the horizon. Furthermore the horizon may move as the individual's 'vision' extends one or more periods beyond the original plan horizon. Changing expectations are not only influenced by subsequent knowledge of the future but also by experiences accumulated during the completed phase of the planning horizon.

The formation of habit and its persistence over time becomes an important influence on the simplification of intertemporal decision making. It acts to make the behaviour of a consumer whose decision making is characterised by foresightedness as well as willingness to revise plans made in the past, strikingly similar to the behaviour of a 'short-sighted' (i.e. myopic) consumer. Hadar (1971) has proven that if an individual maximises a multiperiod utility function, which is constrained by a set of appropriate budget equations, and if the optimal plans are subject to revision after every period, then there exists a one-period utility function which, when maximised subject to a single budget constraint, yields a set of dynamic demand functions that trace out the time paths of the actual amounts consumed (e.g. vehicle usage) and held (e.g. vehicle technology chosen) by an individual.

Hadar's model does not allow for temporal decentralisation of budgets and the possibility of changing tastes. Define the direct utility function as

 $\overline{u}_{j} = \overline{u} [x_{j}, \psi_{j}, z, S]$ 

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where the additional term, S , is a vector of state variables, describing the state of the (current) choice behaviour as a result of past behaviour. In particular it represents stocks of durables such as vehicles (defined by previous choice outcomes - a first order Markov or Polya process) and stocks of habits, including the cumulative effect on present choice of the most recent continuous experience in a state (a renewal process) and habit persistence (a 'latent' Markov process) (Hensher and Wrigley 1986). The variability in S is the mechanism for endogenising taste changes. Without further translation, budget allocations at the beginning of each discrete time interval are no longer separable and hence neither is the intertemporal utility function. Since the complication is due to the presence of state variables, the solution resides in the possibility of making intertemporal models with state variables formally equivalent to intertemporal models without state variables. Since decentralisability simplifies considerably the empirical implementation of intertemporal models (Phlips, 1983) and the validity of this assumption is dependent on the suitable accommodation of state variables, the pay off is high.

Spinnewyn (1979) has shown the formal equivalence using a change of variables, which centres on the definition of consumption cost and wealth. If we can conveniently capture the state variable effect in the notion of rational habit formation, which requires recognition of the dependence of current utility on past habits (a lagged index) and the impact of current decisions on future preferences (a 'leading' index), then we can eliminate the variables by Spinnewyn's method:

'Starting a period with a stock of habits constrains the choice of a consumption plan and thus imposes a cost. The cost of the initial stocks of habits is computed for each period and is subtracted from wealth. Current consumption affects the stock of habits in future periods. The cost of induced consumption through habit formation is added to the cost of current consumption' (Spinnewyn, 1981, 92).

Given decentralisation, the 'cost of the initial stocks of habits' can be measured by a lagged index (one for each variable). It is defined as an appropriate function of the levels of each *exogenous* variable, each weighted by the state dependence parameter ( $\theta$ ) associated with the lagged *endogenous* 'consumption' level (which could be utilisation level, or the binary-valued discrete choice index for each vehicle in the choice set) (Hensher 1986):

$$b_{qt}^{*}(\theta) = \theta^{0} b_{qt}^{*} + \theta b_{q,t-1}^{*} + \theta^{2} b_{q,t-2}^{*} + \theta^{3} b_{q,t-3}^{*} + \cdots = \sum_{r=0}^{t-1} \theta^{r} b_{q,t-r}^{*}$$
(16)

where  $b_{2}^{*}(\theta)$  replaces each of the static versions of explanatory variables in equation (13), A similar index can be derived for a leading index. The full summation for a given exogenous variable describes the total reaction of the current choice with respect to the exogenous variable; successive values of  $\theta$  describing the time shape of the reaction. In practice, our data base (four waves of a panel) has censored the information both back in the past and forward into the future, which means that some components of the index are unobserved. This is especially problematic for the lagged index associated with time period one, and the leading index for period four. The issue of initial (and final) conditions is discussed in the method section, but clearly has an important bearing on the capability of an empirical specification to handle Spinnewyn's procedure for eliminating state variables, enabling us to rewrite the non-separable intertemporal utility function so that it becomes weakly separable with respect to the new variables. This approach is preferred to the more common econometric specifications which incorporate lagged endogenous variables, which apart from introducing estimation complications (serial correlation) are in the words of Phlips (1983, 287 note 14)

'an optical illusion, due to the use of a discrete approximation in the measurement of state variables'.

The study of consumer durables as a discrete choice amongst mutually exclusive and collectively exhaustive alternatives assumes in an intertemporal setting that the difference between desired and actual stocks (using the neoclassical jargon of the aggregate stock adjustment model of consumer durable demand) are not instantaneously or adaptively actualised. The use of depreciation as a basis of continual augmentation is replaced with a durable failure interpretation which requires repair and/or replacement decisions on a usually discontinuous basis.

To establish the relationship, in an intertemporal setting, between the forms of the conditional indirect utility function associated with the discrete choice and the vehicle usage (demand) equation requires a clarification of the notion of duality. Roy's Identity, used to derive the ordinary demand function from a conditional indirect utility function, is taken from static duality theory where the indirect utility function is instantaneous. The standard formula is appropriate in the context of dynamic optimisation when duality is atemporal (i.e. relationships between instantaneous functions), and possibly for temporal duality (i.e. the relationship between the present values of sequences of the corresponding instantaneous parent functions). However when we extend duality to intertemporal duality, the *linking* of instantaneous functions with the corresponding temporal functions, the identity needs modification.

The essential feature of the intertemporal approach is that firstly the duality between the instantaneous indirect utility function and the *total* indirect utility function (or optimal value function) is obtained; and secondly a dynamic analogue of Roy's theorem is used to provide a derivation of the demand (vehicle usage) equation by simple differentiation of the optimal value function. The idea is contained in an obscurely written (and consequently neglected contribution) paper by Cooper and MaClaren (1980). Given the form of the optimal value function, V, and one theorem for mapping V into v, it can be shown that the intertemporal indirect utility function is defined by

$$\mathbf{v}_{j} = \delta \mathbf{V} - \frac{\partial V}{\partial Y^{*}} \left[ (\omega - r) \left( \frac{\partial^{2} V}{\partial Y^{*}_{*2}} \right)^{-1} \frac{\partial V}{\partial Y^{*}_{*}} \right]$$
(17)

and the optimal vehicle usage (demand) equation is

$$x_{j} = -\omega \left[ \frac{\partial V_{j}}{\partial Y_{k}}^{-1} \frac{\partial V}{\partial P_{j}} \right] + \left[ \omega_{-1} \right] \left[ \frac{\partial^{2} V_{j}^{-1}}{\partial Y_{k}} \frac{\partial V}{\partial P_{j}} \right]$$
(18)

where  $\omega$  is the time preference rate, r is the nominal rate of interest, and Y\* is household income minus the annualised cost of vehicle possession and usage.

If we define the total indirect utility (or optimal value) function to have the form in equation (5) then the intertemporal forms of the vehicle usage  $(x_{\cdot})$  model can be obtained by application of (18). The vehicle demand (usage) model is

	×, =	ωx		(	(19)
The	instantaneous	indirect utilit	<pre>/ function becomes</pre>		

$$= \omega \overline{V}$$

(20)

which is identical to the myopic specification (13) except for the inclusion of the intertemporal parameter  $\omega_{*}$   $\omega$  is identified via specification (16), as an amendment to equation (13). The same logic applies to vehicle use.

We now have the theoretical framework for both the static and dynamic interpretations of the household's joint choice of vehicles and rate of use. In the next section we use these results to define the form of the conditional indirect utility expression for each discrete vehicle in the choice set (static equation 13 and the required modification 16 for dynamic choice), and the demand expression for vehicle use (Figure 1).

#### THE ECONOMETRIC FRAMEWORK

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The centrepiece of the econometric system is the intertemporal vehicle utilisation module with critical links from the vehicle choice (SC) and intra-temporal household vehicle use ( $\overline{v}$  VUS) modules (Figure 1). The use module is specified as a panel-based analogue of a simultaneous equations system. The advantage of this approach over the analogy with a pooling method derived from the time series of cross-sections is that it treats each wave of observations as a more extended set of data on the same observation; whereas the time series of cross-sections approach views each wave as a set of new measurements on the same observations. When the number of waves is small and the number of observations is large, pooling is much less attractive since the flexibility gained by increasing the sample size to 4Q.

The Discrete-Choice Module

The conditional indirect utility expression associated with each vehicle in the feasible choice set, equation (13), can be embedded in a nested-logit model of vehicle choice. Simplifying the notation by ignoring the nonlinear-in-parameter specification of the conditional indirect utility function, the three discrete choices of vehicle type mix (v), body mix (m) and quantity (n) are embodied in the conditional indirect utility function as

$$V_{\text{ymn}} = \beta^{\prime} W_{\text{ymn}} + \alpha^{\prime} Y_{\text{mn}} + \gamma^{\prime} Z_{n}, \qquad (21)$$

with  $W_{vmn}$ ,  $Y_{mn}$  and  $Z_n$  denoting the attributes specific to the (v,m,n)<sup>th</sup> vehicle type, the (m,n)<sup>th</sup> body mix and the n<sup>th</sup> fleet size respectively. The nested logit model is

$$P_{vmn} = \frac{\frac{V_{vmn}}{(1-\sigma)}}{\frac{\Sigma}{\Sigma} - \frac{V_{v'mn}}{(1-\sigma)}} \frac{\sum_{z \in v'} \frac{V_{v'mn}}{(1-\sigma)}}{\sum_{z \in v'} \frac{\Sigma}{v'm'n/(1-\sigma)}} \frac{\frac{1-\sigma}{1-\delta}}{\sum_{z \in v'} \frac{V_{v'm}}{(1-\sigma)}} \frac{\sum_{z \in v'} \frac{V_{v'm'n}}{(1-\sigma)}}{\sum_{z \in v'} \frac{\Sigma}{v'm'n'/(1-\sigma)}} \frac{\sum_{z \in v'} \frac{V_{v'm'n'}}{(1-\sigma)}}{\sum_{z \in v'} \frac{\Sigma}{v'm'n'/(1-\sigma)}} \frac{V_{v'm'n'/(1-\sigma)}}{\sum_{z \in v'} \frac{V_{v'm'n'}}{(1-\sigma)}} \frac{V_{v'm'n'/(1-\sigma)}}{\sum_{z \in v'} \frac{V_{v'm'n'}}{(1-\sigma)}} \frac{V_{v'm'n'/(1-\sigma)}}{\sum_{z \in v'} \frac{V_{v'm'n'/(1-\sigma)}}{(1-\sigma)}} \frac{V_{v'm'n'/(1-\sigma)}}{\sum_{z \in v'} \frac{V_{v'm'n'}}{(1-\sigma)}} \frac{V_{v'm'n'/(1-\sigma)}}{\sum_{z \in v'} \frac{V_{v'm'n'}}{(1-\sigma)}} \frac{V_{v'm'n'/(1-\sigma)}}{\sum_{z \in v'} \frac{V_{v'm'n'/(1-\sigma)}}{(1-\sigma)}} \frac{V_{v'm'n'/(1-\sigma)}}{(1-\sigma)} \frac{V_{v'm'n'/(1-\sigma)}}{(1-\sigma)} \frac{V_{v'm'n'/(1-\sigma)}}{(1-\sigma)}} \frac{V_{v'm'n'/(1-\sigma)}}{(1-\sigma)} \frac{V_{v'm'n'/(1-\sigma)}}{(1-\sigma)}} \frac{V_{v'm'n'/(1-\sigma)}}{(1-\sigma)} \frac{V_{v'm'n'}}{(1-\sigma)} \frac{V_{v'm'n'}}{(1-\sigma)} \frac{V_{v'm'n'}}{(1-\sigma)} \frac{V_{v'm'n'}}{(1-\sigma)} \frac{V_{v'm'n'}}{(1-\sigma)} \frac{V_{v'm'n'}}{(1-\sigma)} \frac{V_{v'm'n'}}{(1-\sigma)} \frac{V_{v'm'n'}}{(1-\sigma)} \frac{V_{v'm'n'n'}}{(1-\sigma)} \frac{V_{v'm'n'}}{(1-\sigma)} \frac{V_{v'm'n'n'}}{(1-\sigma)} \frac{V_{v'm'n'n'}}{(1-\sigma)} \frac{V_{v'm'n'n'}}{(1-\sigma)} \frac{V_{v'm'n'n'}}{(1-\sigma)} \frac{V_{v'm'n'n'}}{(1-\sigma)} \frac{V_{v'm'n'n'}}{(1-\sigma)} \frac{V_{v'm'n'n'n'}}{(1-\sigma)} \frac{V_{v'm'n'n'n'}}{(1-\sigma)} \frac{V_{v'm'n'n'n'}}{(1-\sigma)}$$

This can be simplified as:

$$P_{v,mn} = P_{v,mn} \cdot P_{m,n} \cdot P_{n}$$
(24)

$$P_{v|mn} = \frac{\exp(\beta' u_{v|mn})}{\sum \exp(\beta' u_{v'|mn})}$$
(25)

$$P_{m|n} = \frac{\exp(\alpha' Y_{mn} + \frac{1-\sigma}{1-\delta} I_{mn})}{\sum \exp(\alpha' Y_{m'n} + \frac{1-\sigma}{1-\delta} I_{mn})}$$
(26)

$$P_{n} = \frac{\exp\left(\gamma^{\prime} Z_{n} + (1 - \delta)J_{n}\right)}{\sum \exp(\gamma^{\prime} Z_{n} + (1 - \delta)J_{n})}$$
(27)

$$I_{mn} = \log \sum_{k} \exp \left(\beta' W_{k}, mn\right)$$
(28)

$$J_{n} = \log \sum_{m'} \exp \left( \alpha' Y_{m'n} + \frac{1-\sigma}{1-\sigma} I_{m'n} \right)$$
(29)

A sufficient condition for a nested logit model to be consistent with individual utility maximisation is that the parameters  $(1-\sigma)/(1-\delta)$ ,  $1-\delta$  of inclusive values I and J be in the unit interval and not decline as we move to higher-level decisions (Hensher and Johnson 1981, McFadden (1982). The type mix choice models are specified using a set of unranked alternatives comprising the chosen vehicle and 10 randomly generated alternatives of the same body type (mix) from the universal finite set of over 4000 vehicles (defined by make-model-vintage-body type and transmission). The body mix and quantity choice models are defined on the universal finite ranked set of alternatives, defined as the relevant set of body-mixes (sedans, station wagons etc.) as conditioned on fleet size, and the full set of fleet sizes (0, 1, 2, more than 2).

The type mix choice model is estimated by BLOGIT (Hensher 1985) to obtain starting values from a linearised (in parameters) specification of (13) for input into the estimation of the non-linear form. The calculated inclusive values from type mix choice are then included in a full information maximum likelihood nested-logit (FIML-NL) estimation of the body-mix and fleet size choices. The FIML-NL does not require nonlinear parameter estimation, since the unit price of vehicle use is not a direct influence on body mix or fleet size. It is not feasible to apply FIML-NL to all three vehicle choices since the type choice model is an unranked set, which for FIML would involve an unmanageable choice set of over 4000 vehicles. Randomisation is not possible. Details of the exact specification of choice sets and structural relationship between decisions in the tree are given in Hensher (1986) and Hensher et al. (1985c). Alternative ways of modelling composition choice are discussed in Hensher (1985b, 1985d).

There are (at least) three econometric ways of extending the myopic discrete-choice model to an inter-temporal context. Approach A involves estimating wave-specific models (i.e. myopic forms) and using the estimated choice probabilities to identify a choice sequence probability. Although the approach can include exogenous variables to represent previous period outcomes or propensities to occupy states in previous periods, strong assumptions such as zero serial correlation are invoked. This approach has been used in Hensher and Le Plastrier (1985) and Mannering and Winston (1985).

In Approach B the data is pooled with inter-period linkages built in through a lagged index (equation 16), one for each exogenous variable. The lagged index is defined as a weighted sum of each period's level of the variable with the weight given as the stationarity parameter  $\theta$  (to a power of the time periods back from the current, with the current power = 0) associated with a lagged endogenous choice dummy variable. This index is a way of handling state dependence without the serial correlation attributable to right-hand side lagged endogenous variables. The index (as mentioned in the previous section) serves also as a mechanism for adjusting the current levels of 'consumption determinants' to allow for 'stock' effects.

Approach C treats the data as an explicit sequence wherein the likelihood function associated with the choice sequence probability has two major components, one which accounts for the time invariant influences (including the initial conditions) and the other which incorporates the time varying influences. The association between states (in a sequence) may be due to an intrinsic characteristic of the state that changes the likelihood of that state, but it may also occur because some unmeasured and unchanging set of characteristics of an individual causes observed states to persist. The latter phenomenon is heterogeneity (see Hensher and Wrigley 1986). The separation of the time-varying and time nonvarying components provides the formal mechanism for explicitly handling heterogeneity (within and outside of the sample period).

The method increases in complexity as we move from Approach A through to Approach C. The essential features of Approach B are summarised below with more detail given in Hensher (1986) for Approach B and Smith, Hensher and Wrigley (1985) for Approach C. The critical issues in a dynamic (inter-temporal) specification are associated with proper allowance for

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true state dependence (also called feedback or cumulative inertia), nonstationarity (varying choice probabilities over time) and the presence of heterogeneity which can distort the role of the intertemporal relationships. Approaches (B) and (C) provide differing ways of addressing these issues. Approach B is a practical approach for large discrete choice sets with many variables. The approach summarised below is implemented at each level of the nested set of decisions, with an inclusive value carried forward from type mix choice and an inclusive value for body mix estimated directly in the FIML-NL model of body mix-fleet size.

## The approach (B) model is summarised in (30) to (33). $\vec{v}_{qt} = \beta b *_{qt} (\theta) + \epsilon_{qt}$ , $q = 1, \dots, Q; t = 1, \dots, T.$ (30)

### with $y_{qt} = 1$ if $\overline{V} > 0$ = 0 if $\overline{V}_{qt} \le 0$ ... $b_{qt}^{+}(\theta) = as$ defined in (16)

 $\varepsilon_{qt} = \theta^t \alpha_{q0} + w_{qt}$ 

# $W_{qt} = \frac{\overline{\xi}_{qt}}{1 + 0L}$ (32)

(31)

# $\alpha_{q0}^{\alpha} = \beta \sum_{z=0}^{\alpha} \theta_{q,z=z}^{q} = \varepsilon_{q}(\tilde{V}_{q0}).$ (33)

where V

is the conditional indirect utility of an alternative associated with individual q in period t

# Y is the binary valued index taking the value 1 for the chosen alternative and zero otherwise.

 $b_{qt}^{\pm}(\theta)$  is a lagged index operator conditioned on the state

dependence parameter 
$$\theta$$
 associated with a lagged endogenous  $\overline{V}$  (i.e.  $\overline{V}$  =  $2\overline{V}$  =  $4\overline{V}$  =  $4\overline{V}$  =  $4\overline{V}$ 

$$q_{\mu}t \rightarrow i$$
  $(t = 0)$   $qt = 0$   $qt \rightarrow i$   $(t = 1) \in T$  and

 $_{qt}^{w}$  is the traditional error term with a suitable lag (L) operator.

The random component,  $\varepsilon_{qt}$ , includes an initial conditions element,

 $\theta^{\dagger} \alpha_{a0}$  to recognise the presence of left censoring. Subscripting by q

means that prior to the sample origin, individuals have differing 'experiences' (which may be grouped into a manageable set of homogenous classes), and that failure to accommodate these individual-specific differences is a failure to account for one element of heterogeneity. Two strategies are adopted to handle the initial conditions problem: we can include a set of group-specific constants to partially account for the heterogeneity of the initial conditions, and can adjust for heteroscedasticity (a special case of heterogeneity) due to the variation in  $\theta^{t}$ . Two-stage estimation is required to identify the optimal value of  $\theta$ , which is required in the calculation of the correction for heteroscedasticity so that the random term has equal variance for each observation.

In stage one we estimate myopic models for Waves 3 and 4, chosen because they are richer in observed lagged data than earlier waves. Two separate models are required to solve for the value of  $r(=\sigma^2_{\alpha}/\sigma^2_{w})$  required to obtain the correction weight:  $(\theta^{2t}_{r} + 1)^{\frac{1}{2}}$ . The final  $\theta$ , which is invariant with each wave, a necessary condition for a general lag operator, is likely to be closest to the result obtained using Wave 4 with a grid

search method, selecting  $\theta$  which produces the lowest log-likelihood at convergence. The second stage involves the pooled data with all variables (right hand and left hand side) corrected for heteroscedasticity. Further refinement of  $\theta$  can be allowed in this second stage. The final parameter estimates are consistent but not fully efficient, thus t-statistics must be interpreted as upper estimates. The selectivity correction variables can be calculated exactly as done for the myopic model, except now the estimated parameters are drawn from the pooled model. Choice sequence probabilities can be readily calculated as well as the usual choice elasticities.

#### The Intra-Temporal Vehicle Use Module

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f the iance We have identified three approaches to studying household vehicle usage, referred to as the 'pooled vehicles-in-household' approach (Hensher and Smith 1986), the 'vehicle-level' approach (Hensher 1984) and the 'vehiclesin-household' approach (Hensher 1985a, Hensher et al. 1985). The first approach views the household as the observational unit with vehicles in multiple-vehicle households pooled and represented by a set of appropriately combined attribute levels. The second approach defines the household vehicle as the observational unit, with the influence of one vehicle's usage on that of another accounted for by the exogenous specification of the other vehicle in the household as the observational unit but allows endogenously the usage of each vehicle to depend on the use of other vehicles in the household.

When vehicle usage is studied separately from vehicle choice, we can (in the long run) treat vehicle fuel efficiency and petrol cost per kilometre as endogenous influences on vehicle use, highlighting the opportunities to adjust levels of energy consumption via changing the household's vehicle technology. This approach is outlined in Hensher (1985a). An alternative way of recognising and handling the endogeneity of vehicle attributes or vehicle utilisation is via a vehicle choice model which produces a more general index of portfolio endogeneity, as outlined in Hensher et al. (1985). The latter is the essence of the method used in the intratemporal model system which links with the intertemporal vehicle level module.

Formally, the intra-temporal vehicle use module is a system of continuous choice equations with correlated error terms. It is summarised in (34).

 $\frac{\nabla K M_1}{\nabla K M_2} = \frac{\beta_1 + \vartheta_1 x_1 + \lambda_1 Y_1 + \vartheta_1 Z_1 + Y_1 U_1 + \alpha_1 R_1 + \sigma_1 S C_1 + \xi_1}{\theta_2 Z_2 + \lambda_2 Y_2 + \vartheta_2 Z_2 + Y_2 U_2 + \alpha_2 R_2 + \sigma_2 S C_2 + \xi_2}$ 

(34)

 $VKM_{\downarrow} = \beta_{\downarrow} + \partial_{\downarrow}X_{\downarrow} + \lambda_{\downarrow}Y_{\downarrow} + \theta_{\downarrow}Z_{\downarrow} + Y_{\downarrow}U_{\downarrow} + \alpha_{\downarrow}R_{\downarrow} + \sigma_{\downarrow}SC_{\downarrow} + \xi_{\downarrow}$ 

where  $X_v$  is a vector of vehicle possession status attributes

 $Y_{\mathbf{v}}$  is a vector of vehicle-specific characteristics

 $Z_{\rm V}$  is a vector of household socio-economic spatial location and financial characteristics

 ${\tt U}_{\tt V}$  is a vector of vehicle use variables, specific to vehicle  ${\tt v}$ 

R<sub>v</sub> is a vector of vehicle variables. specific to all vehicles. ≠ v

 $\theta,\ \beta,\ \partial_{\alpha},\ \lambda,\ \gamma,\ \alpha,\ \sigma$  are parameters to be estimated.

The vehicle utilisation model is defined on all vehicles used by the household during a specified *period*, such as the 12-month period prior to the point of holdings. The joint modelling of vehicle choice and vehicle use has to recognise the role of vehicles held during the period of vehicle use but which were disposed prior to the point of defining vehicle holdings. The disposed vehicle(s) are included in the set of vehicles in the use module so that their use has the necessary influence on the use of vehicles currently held. The period of time during the specified use period (12 months) that each vehicle is in the household (ranging from 1 to 12 months) is included as an explanatory (shift) variable in the relevant usage equation.

The vehicle use module has to be estimated separately for each level of vehicle quantity. The inclusion of disposed vehicles raises the question of how to view them; should they be considered a separate vehicle or in the situation of replacement, suitably combined with the acquired vehicle? The resolution is not unambiguous. We adopt the following strategy: where a disposed vehicle is replaced by a vehicle (almost immediately) that is to be used by the same person in the household, we define the pair of vehicles in the replacement as a single vehicle, weighting vehicle attributes appropriately. Where a disposed vehicle was associated with a different decision unit in the household to that associated with the acquired vehicle, we treat the disposed and acquired vehicles as separate entities. Unambiguously a disposed vehicle with no acquisition is counted as one vehicle. Hence our definition of household fleet size is non-standard, and arises as a consequence of joint modelling of a point construct and a period construct. Existing studies which have modelled this relationship have failed to account for this important issue (i.e. Train 1985, Mannering and Winston 1985). Only in the special circumstance where all vehicles are held the full 12 months does the ambiguity not arise.

The vehicle use equations for multi-vehicle households include as explanatory variables the level of use of other vehicles in the household, and a dummy variable that identifies the presence of a composite vehicle (derived from a replacement). The estimated parameters of the former variable(s) are a measure of the degree of use substitution, the parameter of the latter variable is a measure of the role of vehicle substitution on the use rate of the composite vehicle. This is the first study to have simultaneously considered the influence on use of selectivity, vehicle use substitution and vehicle substitution. Empirical results of Wave 1 are given in Hensher et al. (1985).

Three-stage least squares [3SLS] is used to obtain parameter estimates. 3SLS combines the instrumental variables technique of two-stage least squares [2SLS] (using fitted values of the endogenous right-hand side variables to get 2SLS estimates of all equations), then the residuals of each equation are used to estimate the cross-equation variances and covariances to account for the degree of intercorrelation among the disturbance terms. Generalised least squares parameter estimates are finally obtained, which are more efficient than those of 2SLS.

The Inter-Temporal Vehicle Use Module

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The utilisation level of vehicles will be predicted from the intertemporal vehicle-level module, linked to (a) vehicle choice by the selectivity variable and (b) use of other vehicles in the household by the vehicle-use substitution effect (Figure 1). Each wave is viewed as a structural equation in a simultaneous equations system. Cross-equation (linear) restrictions are imposed and the serial covariance matrix associated with a pooling approach (i.e. a time-series of cross-sections) is replaced with a variance matrix of errors on the structural equations. A limited information maximum likelihood (LIML) method is used to simultaneously estimate the T equations. We allow for initial conditions and heterogeneity, with some exogenous variables able to be correlated with the individual-specific effects, the latter treated as random effects. We specify a reduced-form equation for the initial conditions as well as the T structural equations, giving T + 1 equations in the system. The errors affecting the dependent variable in the initial conditions equation are assumed non-independent of the errors affecting the vehicle usage variable in subsequent periods.

The general model form for vehicle use in each period is given in equation (35), with the functional form of the right-hand side variables conforming with specifications (14) and  $(19)_{-}$ 

$$\frac{7KH_{vt}}{K} = \beta_0 + \sum_{k=1}^{K} \beta_k X_{kvt} + \sum_{k=K+1}^{K+1} \beta_k Z_{kv} + \gamma V K H_{vt-1} + \sum_{l=t+1}^{T} \Delta_t d_t$$

$$+ \sum_{u=1}^{U} \overline{v}_{ut} V K H_{ut} + \sigma_{vt} \widehat{SC}_{vt} + \theta_{vt} \widehat{EE}_{vt-1} + \xi_{vt} \qquad (35)$$

$$\frac{V}{v} = 1_0 \dots p V; \quad t = 1, \dots, T$$

 $\xi_{vt} = \partial_v + w_{vt}$   $x_{kvt} = \kappa_k \partial_v + x_{kvt}^* \quad (k = 1, \text{ and } K-r; v = 1, \text{ and } v;$   $t = 0 \quad \text{and } T)$ 

(36)

(37)

where VKH<sub>vt</sub> is the annual (or part thereof) kilometres associated with household vehicle v in wave t (VKH<sub>vt-1</sub> being the lagged specification or an exogenous lagged index as specified in (16) for discrete choice).

 $X_{kvt}$  is a time varying k<sup>th</sup> observable exogenous influence associated with vehicle v in wave t (e.g. income fuel cost)

 $Z_{kv}$  is a time-invariant  $k^{th}$  observable exogenous influence associated with vehicle v (e.g. household head, vehicle weight)

is an observable wave-specific dummy variable (1.0)

 $\hat{SC}_{uv}$  is the selectivity correction (12)

q\*

EE<sub>vt-1</sub> is an observable estimated exogenous experience effect derived from the immediate period's discrete-choice process. a, is the unobserved individual-specific effect assumed to

be correlated with a subset of the  $X_{kyt}$ 's and  $Z_{ky}$ 's:

$$\begin{array}{l} p \mbox{$2$ im} & \frac{1}{N} & \chi'_{1 \vee t} \partial_{\nu} = 0; \\ N + \infty & \frac{1}{N} & \chi'_{1 \vee t} \partial_{\nu} = 0; \\ p \mbox{$2$ im} & \frac{1}{N} & \chi'_{2 \vee t} \partial_{\nu} = h; \\ N + \infty & \frac{1}{N} & \chi'_{2 \vee t} \partial_{\nu} = h; \\ \end{array}$$

w\_\_\_\_\_ is a wave specific variate independently distributed over

vehicles in households, but with a suitable variance

matrix of errors on T + 1 structural equation

 $x^{*}_{kvt}$  is the part of  $X_{kvt}$  independent of  $\partial_{v}$ 

 $\rm VKH_{ut}$  is the annual kilometres of other vehicles in the household.

with  $\overline{\mathbf{v}}$  a predetermined parameter (see Figure 1)

 $\beta_{*}(\gamma_{\rm B}/\Delta_{\rm e}/\sigma_{\rm B}/\theta_{\rm e})$  are parameters to be estimated.

#### The Complete Model System

The important elements of the model system are (1) the contemporaneous \* interdependence and intertemporal independence of utilisation levels between vehicles, (2) lagged endogenous vehicle kilometres or a lagged index for the same vehicle, (3) the presence of a subset of time variant and time invariant variables that are correlated with the individual-specific effect (4) con-temporaneous linkage of the discrete choices and vehicle use, with discrete choices linked inter-temporally, (5) cross-equation linear restrictions to account for intertemporal correlation of the errors. It is further assumed that the exogenous variables are free of measurement error, that non-stationarity can be introduced, and by treating the individual effects as random effects we overcome the limitations associated with treating them as 'fixed' parameters.

The model system for the total study consists of three linked discretechoice models, respectively for type choice, body-mix and fleet size choice, twelve intra-temporal vehicle use models (three per period for 1, 2, 3 and more than three vehicles) and one inter-temporal vehicle use model. These models form the basis of a scenario model designed to study the impact on energy consumption of a wide range of potential influences. These include the structure of the household, the status of vehicle technology, the financial aspects of vehicle possession and use, and other considerations under partial or complete control of the government and corporate sectors which can be measured by changes in the levels of variables found to influence the household sector's choice of vehicle technology and level of vehicle utilisation. We now turn to the data bases developed for model estimation.

#### THE EMPIRICAL BASE

The data base for the study consists of a four-wave panel of households resident in the Sydney Metropolitan area (SMA) during the period 1981-1985, a vehicle attribute file of all vehicles applicable to the household sector (which only excludes vehicles over 3 tonnes), and the population of SMA vehicle registrations for the same period. The data is specified in discrete time periods of 12 months.

#### The Household Panel

During the period September 1981 to April 1982 an initial sample of households was drawn from the population of the SMA. A 2-stage sampling strategy was used: the area was stratified by single or contiguous local government areas, and within each stratification cell the number of households

was sampled by probability proportional to the number of households in each cell, relative to the total SMA, to ensure an equal chance of selection. At the time of sample selection the 1981 census data had not been released, so we used the 1976 census as our population base. Consequently we obtained some spatial under (in the South-West) and over (in the North-East) representation. In the second wave we used the 81-census to correct for such spatial discrepancy; we sub-sampled the over-represented group and introduced some new households in the west to produce spatial representativeness for both Waves 1 and 2. A comparison of the weighted and unweighted Wave 1 sample was undertaken to test for any attrition bias. The weights were defined as the ratio of population to sample household numbers for each local government area. Simple regression models were estimated for annual household kilometres and number of vehicles, and descriptive statistics (means, standard deviations) calculated for each variable for the weighted and unweighted samples. The results on a Z-score of differences, as reported in Hensher (1986a) suggest that there is no sample bias attributable to deviations from stratified random sampling on all the major influences on vehicle use and possession, although there is strong evidence to support increasing the number . of households in the south-west and reducing the number of households in the north-east. The final sample of 1434 households in Wave 1 satisfies the spatial representativeness criterion and the statistical representativeness of the parameters of relevant influences on the topic under study.

The remaining three waves of data also satisfy these conditions; although there is attrition there is no attrition bias. Details of procedures used to investigate the possibility of attrition bias are given in Hensher (1986a). The final sample sizes for Waves 2 to 4 are respectively 1291, 1245 and 1197. The overall continuation rate is 84%, with attrition being random in the sense that refusals to continue and households which moved out of the closed population of the SMA have no statistically significant influence on the estimated parameters of the influences on vehicle use and possession, or on the measures of central tendency.

The survey instrument is a structured questionnaire administered in the home by a qualified interviewer. Procedural details are summarised in Hensher (1986a) and Hanzal et al (1985). The survey forms for Waves 2 to 4 were essentially identical, with the Wave 1 form including extra detail in order to establish the household's commencement status in relation to all vehicles in the household during the 12-month period prior to the interview date. The main data obtained are summarised in Table 1. The data can be configured in many ways to produce a detailed data base for analysis at the household, the individual or the vehicle level. Examples of use of the data are given in Hensher (1984, 1985a, 1986a), Hensher and Smith (1986), Hensher et al. (1985)

#### The Vehicle Attribute File

Complementing the household data bases for each wave are vehicle attribute files, compiled as independent files. An extensive set of vehicle characteristics (see Table 2) have been obtained for a representative set of vehicles available to the household sector between 1981 and 1985, including all vehicles held by the sample of households. An initial data base was established for use with the 1981 (Wave 1) survey, updated annually to include vehicles introduced in 1982 through to 1985. The 1981 data file contains 3987 vehicles, defined on the basis of make, model, vintage, body type, transmission and engine capacity. Cars (including sedans, coupes, sports and hatchbacks) and station wagons are defined as representative vehicles with represented vehicles assigned to them

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#### MAIN DATA OBTAINED FROM HOUSEHOLD SURVEY TABLE 1

## Vehicle-data (for each vehicle held in 12-month period):

icle-data (for each vehicle held in 12-month per make, model, vintage, body type, status (held full 12 months, acquired, disposed), years in household, precise dates acquired/ disposed, replacement status, registration category (private, household-business, other-business), financial basis of acquisition, purchase price, trade-in price, current market value, transmission, age at acquisition (new, used), time-dependent costs (registration, compuisory.insurance, other-insurance). fuel.cost, other\_costs (maintenance, body repairs, engine and mechanical repairs, tyres, annual loan repayments) no-claim bonus, annual or part thereof kilometres, odometer reading, days off the road for repairs or other reasons, insurance value, tax deductible expenses, age of primary driver, allocation of kilometres to purposes, distribution of non-metropolitan usage by business-non business with vehicle distances,occupancy and towing, overall vehicle occupancy, search and delay costs in acquisition.

# Household-data (for every member in the household at time of interview):

status of each person (male head, female head, son 1 etc.), age. driver's licence status, no. of vehicles registered in person's name, hours worked (full-time, part-time), occupation, period unemployed, self-employed. seeking work, school status (primary high, college-university), part-time student retired, home duties, marital status, income, stability of income, educational attainments ethnic origins, working hours flexibility, lifestyle.

#### Other-data:

expectation of petrol price increases, attitudes on state of economy, household's financial status next year and adjustments in household's stock of vehicles, costs of other major house-related activities, housing loan or rent, house prices (if moved) recontact addresses (of a friend and a relative), details of journey to work for each worker (location, times, costs, modes, alternatives) alternatives).

#### VEHICLE ATTRIBUTES TABLE 2

# Provid automates Vehicle tope (VEHTTED) (N) Number of structures (NCULINO) (R) Traumates of structures (NCULINO) (R) Traumates of structures (NCULINO) (R) Traumates of structures (NCULINO) (R) Diver (DAIVEI (NECKIN) (R) Cathermann type (TRANANISI (D) Number of structures (NCULINO) (R) Cathermann type (CALTANK) (R) Cathermann type (CALTANK) (R) Cathermann type (CALTANK) (R) Newer Gata Mac pensitry (RETAINK) (R) Vehicle Inself (VEHICIATI (R) Cathermann (VENICIATI (R) Prover (VENICIATI (R) Cathermann (VENICIAT Warning traverse (oil prosants, door open, volta, chale, tähonneter, wert reformarie, paanteer see ere merre, hand wermeg lather (UWO), WHD, WN, WNC, WNT, WNF, WNP, WHAI, ID; WHAI, D; WHAI, D; WHAI, D; WHAI, D; WHAI, D; Munber of doors (NDOORS) (R) Front soar spartner werk(FOOORHT) (R) Front door spartner werk(FOOORHT) (R) Front door spartner werk(FOOORHT) (R) Front door spartner werk(FOOORHT) (R) Windser of spartner werk(FOOORHT) (R) Front door spartner werk(FOOORHT) (R) Front door spartner werk(FOORHT) (R) Front door spartner werk(FOOORHT) (R) Front door spartner werk(FOOORHT) (R) Front door spartner werk(FOOORHT) (R) Windser of version (WTOPER) (D) Bestrook ignation (ELECIGN (D) Front subground (TWDFIER) (R) Front Bestrook (TWDFIER) (R) Front Bestrook

N = nomînal, D = dîchotomous, 1 = înterval, R = ratio scaled.

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Other attributes Angistration cost [R] Insurance rating [I] Warranty conditions [N] Years available as a new vehicle [R] Initial release year [1]

which are essentially the same on the abovementioned criteria (e.g. a Mazda 323 DL and GL). Other vehicles (panel vans, utilities, light commercials, camper vans, small trucks) are defined on the same criteria but without represented vehicles. A separate file is maintained on the new and used prices of all vehicles for each of 1981 through to 1985.

This data can be used in a stand-alone context (e.g. as in Hensher and Smith (1984), for classifying vehicles). When combined with registration data, it provides valuable data on the profile of the vehicle population. Its prime role in the current study, however is as the universal (but finite) set of vehicles from which a household selects its chosen vehicles. The set of alternatives in the choice set for type-mix choice modelling are randomly generated from this file; furthermore certain attributes of vehicles that are easier to obtain from sources other than the household survey are mapped into the set of vehicles chosen by the household to provide a rich base of vehicle attributes in the modelling of vehicle choice and vehicle use. Further details on the compilation of the attribute files are given in Hensher and Miller (1983), Hensher and Hanzal (1985a), and Hensher et al. (1985b).

#### Population Vehicle Registration Data

Vehicle registration data are obtained from the New South Wales Department of Motor Transport as a dump of all vehicles on register in NSW as of December of each year. The data are then prepared for the SMA so that it can be related to the vehicle attribute file. The absence of *model* identification makes the process extremely complex, with heavy reliance placed on the tare weights of vehicles, which together with make and vintage (for business and private classification), provides the basis for mapping. The problems and assumptions are set out in Hensher et al. (1985) and Hensher (1984). The registration data are used in the discrete type-choice models to represent exposure to vehicle types, a proxy for information on vehicles and the bandwagon effect. All other things being equal we expect the probability of selecting a particular vehicle type to be higher where their presence in the market is greater (Hensher et al. 1985).

#### POLICY RELEVANCE

The origins of the automobile study stem from the observation that so little is known about the influence that retail petrol prices have on the household's choice of automobile(s) and on the pattern and level of utilisation. The opportunity to study this issue is especially limited by a dearth of reliable data on vehicle usage. With so many other variables of a 'fluid' nature existing to influence the household's overall consumption of nonrenewable fuels, available aggregate efforts to predict levels of energy consumption in the presence of various fue! prices suffer from both the fallacy of composition and the neutralising of important individual-specific effects. Only by concentrating a study at the household level (and analysing data at this level) can we hope to identify the fuller set of influences on vehicle choice and vehicle use, the two key decisions made by households, which determine the level of energy consumed. In adopting this strategy, not only are we identifying the true role of retail petrol prices, for example, we are also revealing a wider range of policy-tools available as possible alternative (or complementary) mechanisms for achieving desired goals with a lesser negative impact on households.

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Petrol prices per se, as a general instrument, can have undesirable distributional implications; to identify these equity aspects requires a knowledge of the household's financial base, the fuel efficiency of vehicles held, the requirements for vehicle use (e.g. the self employed tradesman), and the financial responsibility for vehicle costs (e.g. the household or a non-household business). Such information can only be obtained at the household level and in the current climate of data scarcity by the collection of new data.

Furthermore, to unravel the causality associated with policies which can impact on households in differing ways at different time-distances from the introduction of a policy requires a longitudinal data perspective. For example, increasing fuel prices can be associated with an initial response of reduced usage; subsequently vehicle replacement can be used as the response with usage levels being re-established - even increased - with a more fuel efficient vehicle. Failure to distinguish true intertemporal relationships from persistent inter-household differences (cross-section studies being limited to the latter) will produce spurious (i.e. unaccounted heterogeneity) inferences, even in the presence of a tight a priori theory of causality.

Panel data, as distinct from other more coarse longitudinal designs which use cohorts, enables us to explicitly include the role of state dependence and habit persistence in the policy-sensitive model system. The combination of intertemporal influence and a full set of influences on vehicle choice and utilisation, together with an allowance for the interdependence of these key decisions, *must* improve our understanding of the energy consumption process of households, *must* provide policy advisers (and others) with a richer basket of options (suggesting different ways of achieving the same targets) and *must*, subject to appropriate forecasts of the levels of the relevant exogenous variables (an issue of even more importance in more realistic models of behaviour), provide improved predictions of responses to policy.

Preliminary analysis of Wave 1 data has already highlighted a set of influences on vehicle use hitherto not considered. The most important finding is the determination of the extent of influence on vehicle usage of the presence of a business-registered vehicle in the household fleet. Previous studies have treated all vehicles as if they were privately registered with all costs met by the household. With close to 20% of total household vehicle stock registered in the name of a business and approximately one half of these vehicles provided to households at zero cost (for both possession and use), the remaining 50% being a tax-deductible expense, allowance for this financial privilege, added to the knowledge that one in 3.5 households have access to such vehicles, significantly reduces the petrol price elasticity of demand (Hensher 1985a). Since businessregistered (household and other) vehicles display higher annual kilometres than private vehicles (19454, 17323 and 11900 respectively in 1981), ignoring this trend in such registrations will result in over-optimistic predictions of the amount of energy conserved through a pricing policy which affects the costs of motoring. The potential for vehicle-use substitution in multiple vehicle households (47.8% of households) and for vehicle substitution in all households add further mechanisms for responding to fuel price changes. A more extensive descriptive assessment is given in Hensher and Smith (1986).

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The way the study is used to identify levels of fuel consumed is summarised in Figure 2 (in conjunction with Figure 1). Two central identities which relate fuel consumption to fuel efficiency, utilisation rate, unit (retail) price of fuel and average fuel cost of usage are

quantity of fuel consumed (litres)	(g)	Ξ	fuel efficiency of vehicle technology (litres per_100km) (VEFF)	μ,	rate of vehicle utilisation (vehicl <u>e</u> kilometres per period) (VKM)	(38)
average fuel cost (cents per km) (PTCSKM)		Ξ	unit (retail) price of fuel (cents per litre) (P)	*	VEFF	(39)

If we assume that the rate of vehicle utilisation is a function of average fuel cost (and other variables), and that vehicle fuel efficiency selected by the household is a function of the unit price of fuel, then given the functional interdependencies between (38) and (39), the direct elasticities of fuel consumption with respect to the unit price of fuel and fuel efficiency can be derived (Hensher et al. 1985). The empirical relationships in the model system are between VKM and PTCSKM, and between the probability of selecting a vehicle and VEFF (and maybe PTCSKM). To derive suitable elasticities and to forecast levels of fuel consumed requires us to estimate the vehicle usage and vehicle choice models, where the roles of VEFF, P, and



and PTCSKM are assessed in the context of the full set of influences on household vehicle choice and use behaviour. Given exogenously supplied projections on the levels and distribution of the exogenous variables in the model system (which may be specified as scenarios), we can predict the levels of VKM for each household, identify the probabilities of selecting particular vehicles, and by the application of (40) obtain a prediction of annual litres consumed. Prob<sub>v</sub> and VKM, are endogenous.

γ = Σ Proby [VEFF, VKMy] . ν⇒1

(40)

The emphasis is on a highly disaggregate household-level perspective which does not suffer from the spatial specificity of more conventional 'household-based' aggregate approaches, and which further emphasises intertemporal relationships to accommodate the process of change, which by necessity is temporal. Consequently we view the study as being capable of providing predictions of energy consumption in the household automobile sector over the long term (up to the year 2000) as well as in the short/ medium term. The relative strength of the approach is in the estimates of the model parameters which are in principle more robust measures of preference than are parameters obtained with aggregate data. The validity of any predictions will ultimately be conditioned by the reliability of the exogenously supplied projections of influencing variables. However, given the depth of the model system, the ability to distinguish the influence of particular policy instruments, which is absent in existing studies in Australia and most studies elsewhere, we are able to provide evidence on the relative effectiveness of alternative policy instruments in meeting the defined objectives. The model parameters can be transferred to other urban contexts in Australia. By suitable adjustments using standard procedures (see Hensher and Johnson 1981), and given the availability of data on the exogenous variables, predictions of fuel consumption in urban Australia can be obtained.

The forecasts of fuel consumption are part of a broader based policy perspective (Figure 3) which via a scenario based general equilibrium model of the automobile market incorporating new vehicle supply, used vehicle scrappage and household demand, predictions of vehicle stocks and levels of usage can be obtained.





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The model can be used, for example, to identify the likely effects of the introduction of unleaded petrol, LPG, a maximum national speed limit, and mandated changes to the vehicle emission system. Each of these supply-side actions can be expressed on the demand side by the unit price of fuel, changing vehicle efficiency (even purchase price) and other dimensions of performance (e.g. acceleration, weight). Given external evidence on the effect of reducing speed limits on vehicle kilometres and/or marginal use cost, the change in fuel consumption can be predicted. The effect of differential pricing of leaded and unleaded petrol on fuel consumption can be easily assessed. Further discussion of specific policies is given in Hensher et al. (1985), and in other papers in progress.

#### CONCLUSION

The 'dimensions of automobile demand' study is a contribution to three main areas of research. Firstly it provides an improved modelling capability in studying the influences on vehicle ownership and utilisation decisions in the household sector, so that we can obtain improved predictions of household vehicle holdings by type, vehicle usage by type and fuel consumption. Non-energy policy can also be examined such as the revenue implications of different tax rates on vehicle registration, purchase, maintenance elements, etc.: the implications of changing vehicle technology on manufacturer market share and hence prospects for the automobile industry; and the implications of the changing levels of vehicle ownership on road investment. The range of outputs are of relevance to automobile manufacturers, oil companies, all levels of government, and interest groups (motorist associations, consumer groups, motor traders association).

Secondly, this study places in an intertemporal setting econometric methods of handling the relationship between discrete and continuous choices. In so doing we are able to accommodate the proper relationship between the (derived) demand for consumer durables and the demand for levels of consumption of durables. The failure of the great majority of applied economic studies to treat the two issues jointly is certainly theoretically invalid, and may in due course explain a significant measure of prediction error and erroneous policy. It is intuitively appealing, at the household level, to relate consumer durable choice and the level of consumption temporally since the opportunity to adjust the 'level' of consumer durables in the context of the many issues of interest is restricted by the lumpiness of durables and their cost.

Thirdly, collection of longitudinal data provides a means of identifying the relative strengths and weaknesses of a single cross-section, as well as extending the range of issues that can be studied. This study has generated an extensive and invaluable data base which hopefully can be used in many research contexts as well as providing an exemplary reference point, especially in energy and transport economics, to the value of panel data approaches.

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