Title

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The University of California Transportation Center

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A Structural Model of Vehicle Use in Two-Vehicle Households

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OBJECTIVES

This research is part of the project aimed at developing a model system to forecast demand for clean fuel vehicles in California, conducted by researchers at the University of California, Irvine and University of California, Davis. The objective of the research reported here is to explain annual vehicle miles of travel for each of the two vehicles in two-vehicle households as a function only of household characteristics that can be forecasted using the household sociodemographic updating model being developed as part of the personal vehicle submodel (Brownstone, Bunch and Golob, 1994). The household's choice of the number of vehicles to own and the types of these vehicles, in terms of the class and vintage of each vehicle, are taken as given in this model.

While this model only deals with households that have chosen to own or lease two vehicles, the structure is readily adapted to single-vehicle households. In principle, it is also adaptable to three-vehicle households, but a model of this complexity probably cannot be estimated using the current sample size restrictions from the Wave 1 Personal Vehicle Survey. The recommended approach for expanding the model to three-or-more-vehicle households, described in the Directions for Further Research Section, is to reduce the number of endogenous and exogenous variables by eliminating less important variables and combining vehicle type classes based on similarity in effects found for the two-vehicle case.

Prior research (Hensher, 1985; Hensher, et al., 1992; Mannering, 1983; Mannering and winston, 1985; and Train, 1986) and exploratory analyses conducted on the present Personal Vehicle Survey have revealed that the characteristics of the principal driver -- specifically, gender, age, and employment status -- are important predictors of use. However, exogenous forecasts of principal driver characteristics for individual vehicles in multi-vehicle and multidriver households are not feasible. Consequently, the present model treats principal driver characteristics as endogenous. The only exogenous variables are the vintages and classes of the two vehicles, and household composition and income. The model is similar to previous models of vehicle allocation and use in multi-vehicle households (Mannering, 1983; Hensher, 1985; Train, 1986; and Hensher, et al., 1992) in that separate equations with correlated error terms are developed for each vehicle in the household. It differs from previous efforts, because there are additional equations for principal-driver characteristics that cannot be readily forecast and need to be "solved out" of the problem. The present approach is also believed to be unique because the reduced-form equations needed for forecasting purposes are developed through a structural specification of vehicle allocation to drivers.

DATA

The model in its current state is estimated on 629 households, representing all two-vehicle households in the 1993 "Wave 1 Personal Vehicle Survey" with known vehicle vintage and type for both vehicles, having two or more drivers with known gender. age and employment status, and with both vehicles driven at least 500 miles per year. The available sample is expected to increase through efforts underway to correct missing and inconsistent vehicle information. It is intended that a revised model will be estimated when an augmented sample becomes available.

The present model has eight endogenous variables, defined in Table 1. The two vehicles in each household are arranged such that the newest vehicle in the two-vehicle household is defined as vehicle 1, described by the first four endogenous variables and the first group of vehicle-type exogenous variables. The second, older vehicle is described by the last four endogenous variables and the last group of vehicle-type exogenous variables. If the two vehicles are of the same model year, the order of listing by the respondent is preserved. Vehicle usage is self-reported in terms of "How many miles per year is this vehicle driven?"

Variable	Acronym
Natural log of vehicle miles traveled per year - first (newest) vehicle	$Ln(VMT_1)$
Age of principal driver - first vehicle	Driver Age_1
Gender of principal driver (+ = female) - first vehicle	Driver $Gender_1$
Employment status of principal driver (+ = working) - first vehicle	Driver Empl St_1
Natural log of vehicle miles traveled per year - second vehicle	$Ln (VMT_2)$
Age of principal driver - second vehicle	Driver Age_2
Gender of principal driver (+ = female) - second vehicle	Driver $Gender_2$
Employment status of principal driver (+ = working) - second vehicle	Driver Empl St_2

Table 1: Endogenous Variables

The model has 29 exogenous variables. These exogenous variables can be divided into two blocks: vehicle characteristics and household characteristics. the first block is made up of 20 variables, ten for each of the two household vehicles. These are listed in Table 2. Vintage is collapsed into 14 categories, 1980 - 1993, because of small category frequencies and the desire to avoid outlier effects: all 1970's were recoded to 1980, 1980 and 1981 was combined into 1981. Vehicle class was collapsed into nine categories, eight of which are included in the model (the luxury class is arbitrarily left out as a base category). In going from 14 original classes, similar low-frequency categories were combined: mini-cars was combined with subcompact cars, mid-size and full-size was combined, and mini-sport utility vehicles was combined with compact trucks (both being essentially two-passenger vehicles. Further research is called for to investigate the effects of vintage and vehicle class coding on model results.

The second block of exogenous variables is comprised of the nine household characteristics listed in Table 3. These variables were selected on the basis of theory and univariate regression analyses of vehicle use and on the basis of travel demand theory. Constraining the selection of household variables was the condition that all variables be capable of being forecast in a micro-simulation model based on data from the Panel Study of Income Dynamics (Hill, 1992). The last variable, "Age of Head(s)," was computed as the mean of the ages of spouses or mates in spousal-like households or the age of the single parent or person who can be identified as the major income-earner in multi-adult households. The dummy variable "Retired HH" is set to one if one or both household heads are retired and nether household head is employed or temporarily unemployed; it is possible that another person, perhaps a grown child is employed in a "Retired HH."

Variable	Acronym
Vehicle Age (in years from 1993)	Vehicle Age_p
Mini or subcompact car class	$Type_p$: Subcompact
Compact car class	$Type_p$: Compact
Mid-size or full-size car class	$Type_p$: Mid-/Fullsize
Sports car	$Type_p$: Sports Car
Compact pickup truck or mini sport utility vehicle	$Type_p$: Small Truck
Full-size (standard) pickup truck	$Type_p$: Std. Truck
Full-size (standard) or mini-van	$Type_p$: Van
Full-size or compact sport utility vehicle	$Type_p$: Sport Util. V.
Operating cost per mile (in cents)	Operating $Cost_p$

Table 2: Exogenous Variables for each of the two vehicles (subscript p = 1 or 2)

Variable	Acronym
Number of household members aged 16-20	No. members 16-20 years
Total number of drivers in household	No. of drivers
Number of children in household aged 1 to 5	No. of kids 1 to 5 years
Total number of children in household	Total no. of kids
Household Income $30,000 or less	Income <= $30,000
Household income more than $60,000	Income > $60,000
Household is spousal-like couple	Couple HH
Household head(s) are retired	Retired HH
Mean age of household heads	Age of head(s)

Table 3: Exogenous Variables - Household Characteristics

SPECIFICATION

The model is specified, estimated, and tested using the standard structural equations model (without latent variables), which is given by

$$\mathbf{y} = \mathbf{B}\mathbf{y} + \Gamma\mathbf{x} + \zeta \qquad (1)$$

where y is an mx1 column vector of endogenous variables, and **x** is an nx1 column vector of exogenous variables. Here, m = 8 and n = 29.

The <u>structural</u> parameters are the elements of the matrices:

$\underset{(m \times m)}{B}$ = (8x8) matrix of causal links between the endogenous variables, and

$\underset{(m \times n)}{\Gamma}$ = (8x29) matrix of direct causal (regression) effects from the n = 29 exogenous variables to the m = 8 endogenous variables,

and the error term parameters are the elements of the covariance matrix:

$\underset{(m \times m)}{\Psi} = E(\zeta\zeta'$ = (8x8) symmetric matrix of variance-covariances of m = 8 unexplained, or unique, terms of the endogenous variables.

The model specification can be subdivided into endogenous effects (Beta Matrix in equation system 1), exogenous effects (Gamma Matrix), and error-term variance-covariances (Psi Matrix). Focusing first on the endogenous effects, the hypothesized causal relationships are depicted in Table 4. Conditional on exogenous effects, use is less for vehicles primarily driven by women and older persons, and use is greater for vehicles primarily driven by employed persons. Male principal drivers are more likely to be employed, as are younger principal drivers, and older drivers are expected to be male. These six effects are expected to be identical for the two vehicles, and this is accomplished by equating coefficients in the upper left-hand quadrant of the Beta Matrix with corresponding coefficients in the lower right-hand quadrant of the Matrix. There is also expected to be a strong negative relationship between principal driver genders for the two vehicles, given by the equated reciprocal effects, $\beta_{3,7}$ and $\beta_{7,3}$. The relationships between the ages and employment status of the two principal drivers are not expected to be as strong.

	Influencing Variable							
Influenced variable	Ln (VMT_1)	Driver Age_1	Driver $Gender_1$	Driver Empl St_1	Ln (VMT_2)	Driver Age_2	Driver $Gender_2$	Driver Empl St_2
Ln (VMT_1)		$\beta_{1,2}$ (-)	$\beta_{1,3}$ (-)	$\beta_{1,4}$ (+)				
Driver Age_1								
Driver $Gender_1$		$\beta_{3,2}$ (-)					$\beta_{3,7}$ (-)	
Driver Empl St_1		$\beta_{4,2}$ (-)	$\beta_{4,3}$ (-)					
Ln (VMT_2)						$= \beta_{1,2}$	$= \beta_{1,3}$	$= \beta_{1,4}$
Driver Age_2								
Driver $Gender_2$			$= \beta_{3,7}$			$= \beta_{3,2}$		
Driver Empl St_2						$= \beta_{4,2}$	$= \beta_{4,3}$	

Table 4: Postulated Direct Effects Between Endogenous Variables

The postulated structure of the vehicle-characteristic exogenous effects, shown in a transposed version of the first twenty columns of the (8 by 29) Gamma Matrix of equation system 1, is depicted in table 5A. The hypotheses are developed by allocating household members to vehicle types and vehicle types and household members to activities. For example, it can be expected that there are more male principal drivers of both compact and full-size pickup trucks, and subcompacts and sports cars will have younger principal drivers, while vans and full-size cars will have older drivers. Vans are likely to be driven by unemployed females in households where an employed male is the principal driver of the other vehicle. The major restrictions that we apply in searching out these exogenous influences is that the effects be the same for the two vehicles (coefficient $\gamma_{i,j} = \gamma_{i+4,j+10}$ for i = 1 to 4, j = 1 to 10).

<table>
<tr><td></td><td colspan="8">Endogenous Variable</td></tr>
<tr><td>Exogenous Variable</td><td>Ln (VMT_1)</td><td>Driver Age_1</td><td>Driver $Gender_1$</td><td>Driver Empl St_1</td><td>Ln (VMT_2)</td><td>Driver Age_2</td><td>Driver $Gender_2$</td><td>Driver Empl St_2</td></tr>
<tr><td>Vehicle Age_1</td><td colspan="4" rowspan="10">First vehicle:
vehicle characteristic
effects on VMT and
relationships between
vehicle characteristics and
principal driver characteristics
(relatively dense submatrix,
equated with 2nd vehicle effects)</td><td colspan="4" rowspan="10">Effects of characteristics
of second vehicle on VMT
and principal driver
characteristics
of first vehicle
(relatively sparse submatrix,
initially specified null)</td></tr>
<tr><td>$Type_1$: Subcompact</td></tr>
<tr><td>$Type_1$: Compact</td></tr>
<tr><td>$Type_1$: Mid-/Fullsize</td></tr>
<tr><td>$Type_1$: Sports car</td></tr>
<tr><td>$Type_1$: Small Truck</td></tr>
<tr><td>$Type_1$: Std. Truck</td></tr>
<tr><td>$Type_1$: Van</td></tr>
<tr><td>$Type_1$: Sport Util. V.</td></tr>
<tr><td>Operating $Cost_1$</td></tr>
<tr><td>Vehicle Age_2</td><td colspan="4" rowspan="10">Effects of characteristics
of first vehicle on VMT
and principal driver
characteristics
of second vehicle
(relatively sparse submatrix,
initially specified null)</td><td colspan="4" rowspan="10">Second vehicle:
vehicle characteristic
effects on VMT and
relationships between
vehicle characteristics and
principal driver characteristics
(relatively dense submatrix,
equated with first vehicle effects)</td></tr>
<tr><td>$Type_2$: Subcompact</td></tr>
<tr><td>$Type_2$: Compact</td></tr>
<tr><td>$Type_2$: Mid-/Fullsize</td></tr>
<tr><td>$Type_2$: Sports car</td></tr>
<tr><td>$Type_2$: Small Truck</td></tr>
<tr><td>$Type_2$: Std. Truck</td></tr>
<tr><td>$Type_2$: Van</td></tr>
<tr><td>$Type_2$: Sport Util. V.</td></tr>
<tr><td>Operating $Cost_2$</td></tr>
</table>

Table 5A: Postulated Direct Effects from the Exogenous Variables
Part 1 - Vehicle Characteristics
(First 20 Columns of 4 x 29 Gamma Matrix, Transposed)

It is also possible that the characteristics of the first vehicle can affect the VMT and principal driver characteristics of the second vehicle, and conversely. The model was initially specified by setting all such cross-vehicle effects to zero. Tests were then conducted to ascertain whether certain cross-vehicle effects were significant after an initial model was calibrated.

The postulated structure of the exogenous effects of household characteristics, shown in a transposed version of the last eight columns of the (9 by 29) Gamma Matrix of equation system 1, is depicted in table 5B. Here, once again, the major restriction involves attempting to equate all effects over the two vehicles (coefficient $\gamma_{i,j} = \gamma_{i+4,j}$ for I = 1 to 4, j = 21 to 29). Examples of hypotheses to be tested include: drivers in high-income households and households of couples are more likely to be employed; VMT is higher in households with driver-aged young persons and in high-income households; principal drivers are younger in households with young children; and drivers in retired households are older and not employed (although some drivers in households in which the head or heads are retired, such as adult children living with their parents, are employed).

<table>
<tr><th></th><th colspan="8">Endogenous variable</th></tr>
<tr><th>Exogenous Variable</th><th>Ln (VMT_1)</th><th>Driver Age_1</th><th>Driver $Gender_1$</th><th>Driver Empl St_1</th><th>Ln (VMT_2)</th><th>Driver Age_2</th><th>Driver $Gender_2$</th><th>Driver Empl St_2</th></tr>
<tr><td>No. members 16-20 years</td><td colspan="4" rowspan="9">Effects of household characteristics on VMT and principal driver characteristics of first vehicle (equated across the two vehicles)</td><td colspan="4" rowspan="9">Effects of household characteristics on VMT and principal driver characteristics of second vehicle (equated across the two vehicles)</td></tr>
<tr><td>No. of drivers</td></tr>
<tr><td>No. of kids 1 to 5 years</td></tr>
<tr><td>Total no. of kids</td></tr>
<tr><td>Income <= $30,000</td></tr>
<tr><td>Income > $60,000</td></tr>
<tr><td>Couple HH</td></tr>
<tr><td>Age of Head(s)</td></tr>
<tr><td>Retired HH</td></tr>
</table>

Table 5B: Postulated Direct Effects from the Exogenous Variables
Part 2 - Household Characteristics
(Last 9 columns of 4 x 29 Gamma Matrix, Transposed)

Finally, the hypothesized Psi Matrix unique-term variance-covariance structure is depicted in Table 6. The freely estimated main diagonal variances produce R^2 values for each endogenous variable when compared to the variances of the endogenous variables. The sub-diagonal covariances specify that the unique, or error, terms of the three of the endogenous variables for the two vehicles should be positively correlated; what is not explained about a variable for one vehicle should be correlated with what is not explained about the same variable for the other vehicle. There is expected to be insignificant covariance between the unexplained portions of the employment status of the two principal drivers

	Endogenous Variable							
Endogenous variable	Ln (VMT_1)	Driver Age_1	Driver $Gender_1$	Driver Empl St_1	Ln (VMT_2)	Driver Age_2	Driver $Gender_2$	Driver Empl St_2
Ln (VMT_1)	$\psi_{1,1}$							
Driver Age_1		$\psi_{2,2}$						
Driver $Gender_1$			$\psi_{3,3}$					
Driver Empl St_1				$\psi_{4,4}$				
Ln (VMT_2)	$\psi_{5,1}$ (+)				$\psi_{5,5}$			
Driver Age_2		$\psi_{6,2}$ (+)				$\psi_{6,6}$		
Driver $Gender_2$			$\psi_{7,3}$ (+)				$\psi_{7,7}$	
Driver Empl St_2								$\psi_{8,8}$

Table 6: Postulated Endogenous Variable
Unique (Error) Term variance-covariances

ESTIMATION RESULTS

Estimation Method

The structural equations are estimated using the normal-theory maximum likelihood method (Bollen, 1989). Because four of the eight endogenous variables are dichotomous, the coefficient estimates will be consistent, but the estimates of parameter standard errors for certain coefficients and the overall model goodness-of-fit will be biased (Bentler and Bonett, 1980). Unbiased estimates can be generated using the asymptotically distribution-free weighted least squares method (Browne, 1982, 1984), but this requires a much larger sample size. (The rule-of-thumb is that the sample size must be at least three times greater than the number of free entries in the asymptotic variance-covariance matrix of the correlation matrix, the fourth order moments; with 36 variables, this requires approximately 2,000 observations.) However, ML estimates have been shown to be fairly robust (Boomsma. 1983), and the two endogenous variables of most interest are continuous.

Model Fit

The structure of the final model is basically in accordance with the hypotheses depicted in the previous tables, with some exceptions. The model fits extremely well according to all goodness-of-fit criteria. The chi-square distributed, -2 log likelihood ratio is 151.30 with 198 degrees of freedom, corresponding to a probability value of 0.994. Thus, the model *cannot* be rejected at the p = .05 level. The estimated R^2 value for VMT of the first (newest) vehicle is 0.129, and that of the second (oldest) vehicle is 0.171; The conclusion is that usage of the second vehicle in two-vehicle households is more readily explained.

Hypotheses of significant effect were accepted at a critical level less than that of p = .05 at this stage in the analysis, because it is expected that future model runs will be conducted with larger sample sizes due to the rectification of missing or inconsistent vehicle class and vintage data. Also, all postulated direct effects on the two usage variables which were of the anticipated sign and significant at the p = .10 level were included in the final model in an attempt to maximize the explanation of vehicle use for forecasting purposes. Nested model chi-square difference tests were used to test the hypotheses of coefficient equalities across the two vehicles. Most of these equality hypotheses were accepted.

Endogenous Variable Structure

The estimated direct effects between endogenous variables are listed with their *t*-statistics in Table 7. Five of the six postulated effects for each vehicle are highly significant and consistent across the two vehicles. However, the effect of principal driver gender on VMT is more complex than anticipated.

	Influencing Variable							
Influenced variable	Ln (VMT_1)	Driver Age_1	Driver $Gender_1$	Driver Empl St_1	Ln (VMT_2)	Driver Age_2	Driver $Gender_2$	Driver Empl St_2
Ln (VMT_1)		**-.0087** **(-5.39)**	-.258 (-4.34)	**0.225** **(4.87)**				
Driver Age_1								
Driver $Gender_1$		**-.0029** **(-3.48)**					**-.847** **(-18.8)**	
Driver Empl St_1		**-.0048** **(-5.32)**	**-.157** **(-7.47)**					
Ln (VMT_2)			0.173 (3.63)			**-.0087** **(-5.39)**		**0.225** **(4.87)**
Driver Age_2								
Driver $Gender_2$			**-.847** **(-18.8)**			**-.0029** **(-3.48)**		
Driver Empl St_2						**-.0048** **(-5.32)**	**-.157** **(-7.47)**	

Table 7: Estimated Direct Effects Between Endogenous Variables
(*t*-statistics in parentheses)
(Equated coefficients in **bold**)

The most effective structure dictates that the gender of the principal driver of the first vehicle is the best predictor of VMT on the second vehicle: If the first principal driver is female, the VMT of that vehicle is less and the VMT of the second vehicle is greater; the gender of the second vehicle's driver being unrelated to that vehicle's VMT. As anticipated, there is a strong link between the genders of the two principal drivers, but no significant link between the ages and employment status.

Effects of the Exogenous Variables

The estimated direct effects from the exogenous variables are listed along with their *t*-statistics in Tables 8A and 8B. The effects of the vehicle characteristics are given in Table 8A. Eleven of the effects for each vehicle are equivalent for the two vehicles, and these are shown in Table 8A in bold. Thirteen effects, eight for vehicle 1 and five for vehicle 2 are unique to each vehicle. Additionally, more cross-vehicle effects were found than expected. Most of these cross-vehicle effects represent influences of the type of the household's *second* vehicle on the use and driver allocation of the *first* vehicle.

Regarding VMT, standard trucks and compact cars are driven less, controlling for all other factors, regardless of whether they are first (newer) or second (older) vehicles. But for small trucks, the negative effect on VMT is stronger for first vehicles than for second vehicles. Also, the relationship between vehicle age and VMT is much stronger for second vehicles than for first vehicles. In addition, a newer first vehicle or one that is a sport utility vehicle implies that usage is shifted away from the second vehicle, while a first-vehicle sports car implies that usage is shifted toward the second vehicle. And if the second vehicle is a van or a mid- or full-size car, usage is shifted away from the first vehicle. These cross-vehicle effects on use appear to capture type specialization. The more general-purpose vehicles (vans and large cars) capture a larger share of a household's driving needs than do more special-purpose vehicles (compact cars, trucks, and sports cars).

	Endogenous Variable							
Exogenous Variable	Ln (VMT_1)	Driver Age_1	Driver $Gender_1$	Driver Empl St_1	Ln (VMT_2)	Driver Age_2	Driver $Gender_2$	Driver Empl St_2
Vehicle Age_1	*-.0122* *(-1.28)*				*0.0195* *(1.84)*			
$Type_1$: Subcompact		**-.925** **(-1.74)**	*-.0383* *(-1.83)*			*1.75* *(2.14)*		
$Type_1$: Compact	**-0.0654** **(-1.35)**							
$Type_1$: Mid-/Fullsize	*0.112* *(1.49)*		**0.0189** **(1.60)**	**-.0576** **(-2.08)**				
$Type_1$: Sports car		*-1.98* *(-1.70)*		*0.118* *(2.00)*	*0.129* *(1.29)*			
$Type_1$: Small Truck	*-.3300* *(-3.45)*		**-.0963** **(-3.17)**					
$Type_1$: Std. Truck	**-.125** **(-1.63)**	**2.38** **(3.09)**	**-.0820** **(-2.77)**					
$Type_1$: Van		**0.999** **(1.30)**	*0.0304* *(1.55)*					
$Type_1$: Sport Util. V.			**-.0256** **(-1.40)**		*-.106* *(-1.21)*			
Operating $Cost_1$			*-.0146* *(-2.07)*	**-.0186** **(-2.60)**				
Vehicle Age_2				*-.0070* *(-1.78)*	*-.0408* *(-4.77)*	*0.201* *(2.07)*	*-.0064* *(-2.82)*	*0.0102* *(2.29)*
$Type_2$: Subcompact		*-1.25* *(-1.81)*				**-.925** **(-1.74)**		
$Type_2$: Compact					**-0.0654** **(-1.35)**			
$Type_2$: Mid-/Fullsize	*-.104* *(-1.35)*			*0.106* *(2.77)*	-0.151 (-2.18)		**0.0189** **(1.60)**	**-.0576** **(-2.08)**
$Type_2$: Sports car		*0.0760* *(1.71)*						
$Type_2$: Small Truck					*-.119* *(-1.33)*		**-.0963** **(-3.17)**	
$Type_2$: Std. Truck					**-.125** **(-1.63)**	**2.38** **(3.09)**	**-.0820** **(-2.77)**	
$Type_2$: Van	*-.188* *(-1.49)*			*0.137* *(2.11)*		**0.999** **(1.30)**		
$Type_2$: Sport Util. V.		*-2.37* *(-1.74)*					**-.0256** **(-1.40)**	
Operating $Cost_2$								**-.0186** **(-2.60)**

Table 8A: Estimated Direct Effects from the Exogenous Variables
Part 1 - Vehicle Characteristics
(*t*-statistics in parentheses)
(Equated coefficients in **bold**; *unique coefficients in italics*)

Regarding driver allocation to vehicle type, if the second vehicle is either a subcompact car or a sport utility vehicle, the driver of the first vehicle is likely to be younger than otherwise expected. If the second vehicle is a sports car, the driver of the first vehicle is likely to be older than expected, a possible "middle age" effect. An older second vehicle indicates that the first-vehicle driver is more likely to be unemployed, and if the second vehicle is a van or a mid- or full-size car, the driver of the first vehicle is more likely to be employed.

Several other direct relationships between principal driver age and vehicle type are consistent across the two vehicles: the principal drivers of subcompact cars are younger, while the drivers of standard trucks, and vans are older, controlling for all other effects. The hypothesis of older drivers for full-size and mid-size cars was rejected. The drivers of first-vehicle sports cars are likely to be younger, as are the drivers of newer second cars.

Driver allocation by gender is also mainly consistent for the two vehicles: drivers of full- and mid-size cars are more likely to be women, while drivers of trucks and sport utility vehicles are more likely to be men, *ceteris paribus*. In addition, older second vehicles tend to be driven more by males, and first vehicles that are higher operating cost or subcompact cars tend to be driven more by males; women are more likely to be drivers of first-vehicle vans.

The direct effects from the household variables are listed in Table 8B. Seven of the direct effects of the household characteristics are equal across the two vehicles, an exceptional result. There are also seven unique effects. The strong relationships between the mean age of the household heads and the ages of the two principal drivers are similar for the two vehicles, but the equality constraint is rejected at the p = .05 level (ΔX^2 = 5.12 with one degree of freedom, indicating that the improvement in the model fit due to releasing the constraint is significant).

	Endogenous variable							
Exogenous Variable	Ln (VMT_1)	Driver Age_1	Driver $Gender_1$	Driver Empl St_1	Ln (VMT_2)	Driver Age_2	Driver $Gender_2$	Driver Empl St_2
No. members 16-20 years					*0.270* *(2.85)*			
No. of drivers			**-.156** **(-2.73)**				**-.156** **(-2.73)**	
No. of kids 1 to 5 years		**-1.04** **(-2.70)**				**-1.04** **(-2.70)**		
Total no. of kids	*0.0655* *(1.93)*					*-1.24* *(-3.33)*		
Income <= $30,000								*-.104* *(-2.07)*
Income > $60,000	**0.137** **(2.74)**			**0.0492** **(2.03)**	**0.137** **(2.74)**			**0.0492** **(2.03)**
Couple HH	*0.0957* *(1.38)*			**0.0500** **(2.29)**				**0.0500** **(2.29)**
Retired HH		**3.68** **(4.53)**		**-.707** **(-16.3)**		**3.68** **(4.53)**		**-.707** **(-16.3)**
Age of Head(s)		*0.814* *(34.0)*				*0.882* *(36.5)*		

Table 8B: Estimated Direct Effects from the Exogenous Variables
Part 2 - Household Characteristics
(*t*-statistics in parentheses)
(Equated coefficients in **bold**, *unique coefficients in italics*)

The only vehicle-consistent direct effect on VMT is a direct positive effect of high income. The number of household members 16-20 years of age causes increased VMT of the second vehicle, but not the first vehicle. In contrast, the total number of children in the household is directly related to increased VMT of the first vehicle, and if a household is comprised of a couple only, VMT of the first vehicle is also higher than otherwise expected, but this is a weak effect.

However, all of the household characteristics will have an indirect effect on VMT through their direct effects on the other endogenous variables, combined with the effects of the endogenous variables on each other. For example, both drivers in households comprised of couples without children are more likely to be employed, and usage is higher for employed drivers. Also if a household is low income, the driver of the second vehicle is more likely to be unemployed, leading to lower VMT for the second vehicle. Thus, the interpretation of the ultimate influences of the exogenous variables on vehicle usage is applied to the total effects (reduced-form equation coefficients), not the direct effects shown in Tables 8A and 8B, because of the multiple paths of causality among the endogenous variables, and this is the subject of the next Section.

Error-term Covariances

The variance-covariance estimates for the endogenous variable unique terms (the Psi Matrix parameters) are listed in Table 9. As expected, there are positive and significant error-term covariances between the VMT for the first and second vehicles, and the unexplained portions of principal driver gender are also significantly correlated. However, the error components of principal driver age and employment status are not significantly correlated. If the covariance term for age is added to the model, its t-statistic is only 0.88, and if the covariance term for employment status is added, its *t*-statistic is only 0.83. The error components of age are probably uncorrelated because of the strong direct effects of the exogenous "Age of head(s)" variable.

	Endogenous Variable							
Endogenous variable	Ln (VMT_1)	Driver Age_1	Driver $Gender_1$	Driver Empl St_1	Ln (VMT_2)	Driver Age_2	Driver $Gender_2$	Driver Empl St_2
Ln (VMT_1)	0.467 (17.3)							
Driver Age_1		44.8 (17.3)						
Driver $Gender_1$			0.125 (15.4)					
Driver Empl St_1				0.116 (17.3)				
Ln (VMT_2)	0.119 (6.80)				0.364 (17.3)			
Driver Age_2						43.1 (17.3)		
Driver $Gender_2$			0.118 (11.0)				0.125 (15.3)	
Driver Empl St_2								0.128 (17.3)

Table 9: Estimated Endogenous Variable Unique (Error) Term Variance-covariances
(*t*-statistics in parentheses)

TOTAL EFFECTS

The total effects of the exogenous variables on the endogenous variables in a structural equations model of this type are given by:

$$T_{yx} = (\mathbf{I} - \mathrm{B})^{-1}\,\Gamma.$$

These are the so-called reduced-form equations. The total effects of the endogenous variable on each other is given by

$$T_{yy} = (\mathbf{I} - \mathrm{B})^{-1} - \mathbf{I}\,.$$

The total effects of the endogenous variables on the endogenous variables are listed in Table 10. The age effects on VMT are significant both within and between vehicles for both principal drivers. Having a younger principal driver on either vehicle means that both vehicles are used more. In contrast, the employment status effects are totally consistent for the two vehicles but there are no cross-effects between vehicles. That is, if the principal driver of one of the vehicles is employed, that vehicle is driven more, but this does not effect the usage of the other vehicle.

The gender effects are also consistent for the first and second vehicle: If the principal driver of either vehicle is a female, that vehicle is driven less and the other vehicle is driven more. The strongest gender effect is from the gender of the first vehicle principal driver to usage of that first vehicle.

	Influencing Variable							
Influenced variable	Ln (VMT_1)	Driver Age_1	Driver $Gender_1$	Driver Empl St_1	Ln (VMT_2)	Driver Age_2	Driver $Gender_2$	Driver Empl St_2
Ln (VMT_1)		-.0066 (-3.85)	-1.04 (-2.96)	0.225 (4.87)		-.0026 (-3.69)	0.880 (2.62)	
Ln (VMT_2)		-.0021 (-3.31)	0.720 (2.66)			-.0078 (-4.74)	-.645 (-2.53)	0.225 (4.87)

Table 10: Total Effects on the Two Usage Endogenous Variables
from the Other Endogenous Variables
(t-statistics in parentheses)

The total effects of the exogenous variables on the usage endogenous variables are listed in Table 11. These are the coefficients of the so-called reduced-form equations for two of the eight endogenous variables. For simplicity, the total effects for the other six endogenous variables are not shown because focus here is on forecasts of vehicle use. These total effects on usage are most efficiently interpreted by comparing the effects of corresponding blocks of exogenous variables between the two vehicles:

Vehicle Ages

Age of the first vehicle indicates a shift from first-vehicle to second-vehicle use, affecting VMT of the first vehicle negatively and VMT of the second vehicle positively. In contrast, age of the second vehicle affects VMT of both vehicles negatively. If a household has an older second vehicle, both the first and second vehicle are likely to be driven less. The influence of age of the second vehicle on use of the second vehicle is the strongest of all of the vehicle age effects; "old clunkers" are much less used.

Vehicle Types

Subcompact cars are driven more as either first or second cars, and if the second vehicle is a subcompact car, the first vehicle in the household is also driven more. Conversely, if the first vehicle in the household is a compact car, the second vehicle is driven less.

Compact cars have approximately average usage.

The primary relationship between mid-size and full-size (standard) cars and usage involves the second vehicle; if it is a mid- or full-size car it is used less.

Sports cars on the other hand demonstrate higher usage only if they are the first (newest) vehicle in the household. Sports cars as second cars have a weaker positive relationship to usage, and there is a moderate effect of first-vehicle sports cars on second-vehicle usage, presumably because the sports car is a special-purpose vehicle.

	Exogenous Variable				
Endogenous Variable	Vehicle Age$_1$	Type$_1$: Subcompact	Type$_1$: Compact	Type$_1$: Mid-/Fullsize	Type$_1$: Sports car
Ln (VMT_1)	-.0122 (-1.28)	0.0414 (2.03)	-.0654 (-1.35)	0.0801 (1.05)	0.0395 (2.41)
Ln (VMT_2)	0.0195 (1.84)	-.0392 (-2.47)	--	0.0136 (1.65)	0.133 (1.33)

Endogenous Variable	Type$_1$: Small Truck	Type$_1$: Std. Truck	Type$_1$: Van	Type$_1$: Sport Util. V	Operating Cost$_1$
Ln (VMT_1)	-.231 (-2.42)	-.0557 (-0.72)	-.0382 (-1.90)	0.0266 (1.48)	0.0110 (1.57)
Ln (VMT_2)	-.0693 (-3.52)	-.0640 (-3.13)	0.0198 (1.43)	-.125 (-1.41)	-.0105 (-2.13)

Endogenous Variable	Vehicle Age$_2$	Type$_2$: Subcompact	Type$_2$: Compact	Type$_2$: Mid-/Fullsize	Type$_2$: Sports car
Ln (VMT_1)	-.0072 (-3.78)	0.0107 (2.07)	--	-.0631 (-.82)	0.0171 (1.61)
Ln (VMT_2)	-.0343 (-4.00)	0.0098 (2.14)	-.0654 (-1.35)	-.176 (-2.54)	--

Endogenous Variable	Type$_2$: Small Truck	Type$_2$: Std. Truck	Type$_2$: Van	Type$_2$: Sport Util. V.	Operating Cost$_2$
Ln (VMT_1)	-.0848 (-4.14)	-.0783 (-3.55)	-.160 (-1.26)	-.0069 (-.37)	--
Ln (VMT_2)	-.0572 (-.641)	-.0908 (-1.17)	-.0078 (-1.26)	0.0215 (1.77)	-.0042 (-2.29)

Endogenous Variable	No. members 16-20 years	No. of drivers	No. of kids 1 to 5 years	Total no. of kids	Income <= $30.000
Ln (VMT_1)	0.0120 (2.73)	0.0248 (2.40)	0.0095 (2.46)	0.0688 (2.03)	--
Ln (VMT_2)	0.306 (3.21)	-.0116 (-1.89)	0.0102 (2.48)	0.0097 (2.73)	-.0235 (-1.90)

Endogenous Variable	Income > $60.000	Couple HH	Retired HH	Age of Head(s)	
Ln (VMT_1)	0.148 (2.96)	0.115 (1.65)	-.193 (-5.62)	-.0077 (-5.99)	
Ln (VMT_2)	0.148 (2.96)	0,0348 (3.78)	-.196 (-5.69)	-.0086 (-6.17)	

Table 11: Total Effects from the Exogenous Variables on the Usage Endogenous Variables (Coefficients of reduced-form equations) (*t*-statistics in parentheses)

Small (compact) pickup trucks (including mini-sport utility vehicles) are consistently driven less, and their presence as a first or second vehicle indicates that the other vehicle in the household is driven less as well. The strongest link is between small trucks and their usage as a first vehicle.

Standard pickup trucks have a usage pattern that is similar to that of small trucks. However, the first-vehicle relationship between usage and standard trucks is substantially weaker than the corresponding relationship for small trucks. Trucks could be combined into a single category in future models.

Vans are driven less as first vehicles and there is some evidence of a shift of usage from a first-vehicle van to the second vehicle. The second-vehicle effects of van ownership on usage are weak.

Finally, full-size and compact sport utility vehicles are driven slightly more than average, and usage appears to be shifted in favor of such a vehicle if it is the newest vehicle in the household.

Operating cost

The total effects of operating cost are opposite for first and second vehicles. Higher operating cost vehicles are driven more if they are the first (newest) vehicle in a household, *ceteris paribus*, presumably a consequence of the improved comfort and safety of new higher operating cost vehicles. However, higher operating cost vehicles are driven less in the case of the second vehicle. This could be an true cost effect.

Household characteristics

The numbers of household members between 16 and 20 years old is a positive influence on VMT of both the first and second vehicle, but the effects on second-vehicle VMT are considerably greater than effects on first-vehicle VMT.

The numbers of drivers in the household has a positive effect on VMT of the first vehicle, but a weak negative effect with on VMT of the second vehicle. However, there is a relatively high standard error on the second vehicle effect, and th hypothesis of a null relationship between number of drivers and second-vehicle VMT can be accepted with the present sample.

The number of children 1 to 5 years old and the total number of children all positively influence VMT of both the first and second vehicle, with the effect of the total number of children being concentrated on VMT of the second (oldest) vehicle.

There is an important positive high-income effect on the VMT of both vehicles, but the effect of low-income is weakly directed toward use of the second vehicle only.

Households comprised of couples exhibit higher vehicle usage, particularly usage of the first vehicle. Conversely, retired households exhibit lower usage of both vehicles.

Finally, vehicle usage is higher for households headed by younger persons.

CONCLUSIONS AND DIRECTIONS FOR FURTHER RESEARCH

Estimation methodology

The anticipated increase in the sample size resulting from an improved vehicle classification algorithm applied to the First Wave Personal Vehicle Survey data will provide more conclusive hypothesis testing, potentially leading to modifications in model specification. With an increased sample size, it might also be possible to use generally weighted least squares estimation appropriate for non-normal endogenous variables. However, the sample size requirements of such an asymptotic method would still require a reduction in the total number of variables, so it would be necessary to combine vehicle type categories and otherwise eliminate marginally effective exogenous variables. This represents a trade-off between model elegance and forecasting capability.

The known biases in the maximum likelihood estimation method are concentrated on coefficient standard errors and overall goodness-of-fit criteria. The intention here is to accept all marginally significant structural links that are theoretically justified in order to optimize forecasting capability, so the failure to reject structural hypotheses is not deemed a major problem. Also, the fit of the model is not in question, so maximum likelihood estimation should suffice if it is not possible to use the alternative method.

Extension to other vehicle ownership levels

It should be possible to extend the model to all other vehicle ownership levels. The model can be easily simplified to the one-vehicle case by using only endogenous and exogenous variables for one vehicle rather than two vehicles.

The endogenous principal driver variables can be treated as exogenous variables because they can be forecasted.

There are several possibilities for more than two vehicles, and these need to be carefully evaluated. One approach is to explode the model structure to add a third vehicle in a manner consistent with the first two vehicles. However, it is likely that sample size for three-vehicle households will not support estimation of such an extended model. The present model contains approximately 60 free parameters, so an extended three-vehicle model might contain 90 or more free parameters. If the rule-of-thumb of six observations per free parameter is applied, the three-sample size called for is in excess of 540 households. This sample size is not feasible with the present survey data.

Another possibility is to add third vehicles to the present model in a summary fashion. This could be accomplished by adding only the VMT of the third vehicle as an endogenous variable (disregarding the third-vehicle principal driver characteristics), and adding vehicle age and operating cost as exogenous variables. The explanation of third-vehicle use would then be confined to household and cross-vehicle effects. The number of third-vehicle variables that could be added to the model will depend on the eventual sample size. The model might be extended to four or more vehicles in a similar manner.

Extension to alternative fuels

The present model is of the "revealed preference" (RP) type. The plan is to extend it to forecast use of alternative-fuel vehicles as well as conventional-fuel vehicles. This will require adding "stated preference" (SP) responses that capture intended differences in use attributed to fuel type. Relevant SP questions are in the currently-available Wave 1 Personal Vehicle Survey conducted in 1993, but there are potentially more valuable SP usage questions in Wave 2 of the Survey, which will be conducted in July-September, 1994. It is prudent to wait for the Wave 2 data, but a preliminary fuel-sensitive model might be estimated on Wave 1 data.

A straightforward extension to alternative-fuels is envisioned: The SP survey tasks provide hypothetical endogenous usage and driver allocation variables, in association with exogenous fuel-type dummy variables and SP design variables.

Use in Forecasting

This model and its future extended versions is logically applied as a marginal change model. For each year, each household's vehicle usage is calculated before and after all annual changes that are forecasted by the dynamic vehicle ownership model and the dynamic household sociodemographic structure forecasting model. Note that even if the models forecast no change in vehicle ownership (number of vehicles or type of each vehicle in the household's fleet) and no change in household characteristics (household composition, employment status, or income), the present model will predict changes in VMT due to aging of the household heads, possible changes in the age categories of children, possible additions to the numbers of drivers in the household, and aging of the vehicles. The change in each vehicle's usage is then applied as a percentage change to the actual base levels of usage reported by the household.

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