THE LIGHT-DUTY-VEHICLE FLEET'S EVOLUTION: ANTICIPATING PHEV ADOPTION AND GREENHOUSE GAS EMISSIONS ACROSS THE U.S. FLEET

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ABSTRACT

With environmental degradation and energy security as serious concerns for most countries, it is important to anticipate how vehicle ownership and usage patterns – and associated petroleum use and greenhouse gas (GHG) emissions – can change under different policies and contexts. This work relies on a stated and revealed preference survey of U.S. households to ascertain the personal-vehicle acquisition, disposal, and use patterns of a synthetic population over time.

In addition to reporting on key summary statistics and behavioral model results using the national sample, this work relies on microsimulation to anticipate future fleet composition, usage, and GHG emissions under different gas price, PHEV pricing, feebate policy, and demographic settings. 25-year simulations predicted the highest market share for PHEVs, HEVs, and Smart Cars under an increased gas price ($7 per gallon) scenario. Results under a feebate policy scenario indicate a shift towards fuel efficient vehicles, but with vehicle miles traveled (VMT) rising, thanks to lower driving costs. The fees collected under the feebate policy significantly exceed rebates distributed to buyers of relatively efficient vehicles (assuming a 30 mi/gal pivot point), suggesting the need for a much higher pivot point, to motivate significant behavioral shifts and a lower pivot point to achieve revenue neutrality, under current sales trends.

Excepting the low PHEV price and feebate policy simulations, all other scenarios predicted a lower fleet VMT. Simulated fleet VMT and GHG emissions lowest under the $7-per-gallon gas-price scenario. The high-density scenario (where job and household densities were quadrupled), resulted in the lowest total vehicle ownership levels, and thus lower VMT and emissions.

As expected, the low-PHEV-price scenario resulted in higher shares of PHEVs, but just negligible GHG emissions impacts (relative to trend). Households with three or fewer members were predicted to be the highest adopters of PHEVs and HEVs across all scenarios. While plug-in vehicles are now hitting the market, their adoption and widespread use will depend on thoughtful marketing, competitive pricing, government incentives, reliable driving-range reports, and adequate charging infrastructure. Though just 29% of survey respondents (weighted to reflect the U.S. population) stated support for a (specific) feebate policy, 35% indicated an interest in purchasing a PHEV if it cost $6,000 more than its gasoline counterpart. This work helps highlight the impacts of various directions consumers may head with such vehicles.

Key Words: Plug-in electric vehicles, personal vehicle fleet, vehicle ownership, microsimulation, travel behavior modeling, greenhouse gas emissions

INTRODUCTION AND MOTIVATION

Per-capita greenhouse gas emissions in the U.S. are four times the world average (WRI 2009), with the transportation sector accounting for close to 30 percent of the nation's total (EPA 2009). A variety of strategies exist to reduce such emissions, including automotive designs, fuel-source alternatives, vehicle and gas pricing policies, and travel-demand management. Light-duty vehicle ownership decisions impact fleet composition directly, total vehicle miles traveled (VMT), fuel consumption, GHG emissions, congestion, tolling revenues, and road safety somewhat less directly (see, e.g., Musti and Kockelman [2010] and Lemp and Kockelman [2010]). Thanks to such linkages, transportation planners, engineers and policy makers should have great interest in accurately forecasting future vehicle fleet attributes.

This study is inspired by Musti and Kockelman's (2010) modeling of the household vehicle fleet in Austin, Texas, over a 25-year period. This work makes use of a very similar microsimulation framework, with embedded transaction, vehicle choice and vehicle usage models, to forecast the U.S. vehicle fleet's composition and associated GHG emissions, from 2010 to 2035, under a variety of policy, technology, and gas-price scenarios. The following sections present recent literature, data collection and model details, as well as the 25-year simulation results. The paper concludes with a summary and recommendations for policy and future work.

PREVIOUS WORK

Most past studies of vehicle ownership have emphasized the impacts of vehicle attributes, household characteristics and environmental variables (like fuel prices and taxes) on vehicle choice decisions. Lave and Train (1979) estimated a multinomial logit (MNL) model for vehicle choice, with household and vehicle characteristics, gasoline prices and taxes as explanatory variables. Manski and Sherman (1980) estimated MNL models for one and two vehicle households and concluded that most vehicle performance attributes have relatively little impact on choice, while price and operating and transaction costs are practically (and statistically) significant. Berkovec and Rust (1985) estimated nested logit (NL) models, and noted that consumers are more likely to stick with past or current vehicle types, rather than replacing with a different type. Findings from these studies are consistent with those of Mannering et al. (2002), Mohammadian and Miller (2003a), Train and Winston (2007), and Nolan (2010).

Neighborhood attributes and owner attitudes can also play substantive roles. Potoglou et al. (2008) found that transit proximity, diversity of land use, and home-to-work distances to be significant determinants of vehicle ownership, after controlling for socio-economic characteristics. Bhat et al. (2009) examined the effect of built environment characteristics, and concluded that neighborhoods high in density of both residential and commercial uses are associated with smaller size vehicles. Zhao and Kockelman (2001) found household size, income, home-neighborhood population density, and vehicle prices to be important predictors of household vehicle counts (by vehicle type).

Choo and Mokhtarian (2004) concluded that consumers' travel attitudes, personalities, lifestyles, and mobility are helpful predictors of vehicle choice decisions. Kurani and Turrentine (2004) concluded that households generally do not pay much attention to a given vehicle's fuel cost (per mile, year, or lifetime) time unless they are operating under tight budgetary constraints; however, they do pay attention to fuel prices (per gallon). Busse et al. (2009) found that market *shares* of *new* vehicles (by fuel economy category) tend to adjust to offset gas-price shifts, while *used*-vehicle *prices* adjust directly. Mannering and Winston (1985) estimated a dynamic model for vehicle choice and use, reflecting past choices. Their results suggest that consumers go for a vehicle with higher brand loyalty, ceteris paribus. Berkowitz et al. (1987) reported inertia effects in (short-run) vehicle use and fuel consumption data, in response to energy-related policies. Feng et al. (2005) estimated a NL choice model coupled with use model and predicted that higher gasoline prices and rising registration taxes as vehicles (and their emissions control technologies) age will lead to emissions reductions.

Vehicle choice and transaction models have been increasingly used for forecasting market shares of alternative fuel vehicles and evaluating climate and energy policies. Mohammadian and Miller (2003b) predicted changes in household size and job status (of household members) to be significant determinants of transaction decisions. Gallagher et al. (2008) concluded that higher gasoline prices and heightened preferences for energy security or environmental protection tend to lead to greater rates of hybrid electric vehicles (HEV) adoption, rather than government incentives (which often come after purchase, in the form of annual-income tax rebates, for example). Musti and Kockelman (2010) estimated Austin's highest future PHEV-plus-HEV share (19% by 2034) under a feebate policy scenario.

This work relies on the growing literature, described above, for specification of behavioral models and the simulated scenarios. The model runs anticipate adoption of HEVs and PHEVs across the U.S. personal-vehicle fleet over the next 25 years, under high gas prices, feebate policy settings, and other scenarios.

DATA DESCRIPTION

Data were obtained via an online survey issued in the Fall of 2009, using a pre-registered sample of households/respondents from across the U.S., as maintained by Survey Sampling International

(SSI). The questionnaire used by Musti and Kockelman (2010) for collection of Austin area data was enhanced[1] for use in this national on-line survey.

Household Synthesis and Vehicle Ownership Data

Population weights were computed by dividing the sample into 720 categories, based on gender, age, employment and student status, household size and household income categories. The ratios of counts from the 2008 American Community Survey's (ACS 2008) microdata sample to the survey's sample counts were normalized. Households in the survey sample were scaled up in proportion to their corresponding weights, to construct a synthetic U.S. population of workable size (50,016 synthetic households, to represent 115-million year-2010 households).

The survey included questions on respondents' current and past vehicle-holdings and vehicle-use details, stated future vehicle choice elections, opinions on climate and energy policies, and demographics. In the stated preference (SP) section, respondents were presented with 12 vehicle choices covering wide range of price, fuel economy, and body types[2] under four different scenarios. PHEVs[3] were assumed to have a 30-mile[4], all-electric range requiring about 250 watt-hours per mile, with an 11 gallon gas tank resulting in a total range of 500 miles. All other attributes of the PHEV30 matched a Toyota Prius. The four scenarios presented to each respondent consisted of a trend scenario, two increased-gas-price scenarios ($5 and $7 per gallon, fuel costs were provided), and an external-costs scenario (with GHG and other emissions' social-cost impacts estimated for each vehicle [assuming driving distances of 15,000 miles per year, which is typical of new U.S. vehicles])). Other questions included opinions about potential climate and energy policies and the respondents' willingness to adopt advanced vehicle technologies under different fuel-cost and purchase-price scenarios. The final section requested demographic details.

Data Set Statistics

Table 1 compares key demographic variables obtained in the national survey to U.S. ACS data (which rely on 2006 through 2008 averages). The sample's household income is 19 percent lower ($59,882 vs. $71,128) than the national average (perhaps due to the financial crisis that began in 2007). And the average number of vehicles per household is about 15 percent less than the ACS average (similar to the income effect). Nevertheless, the share of online respondents holding a bachelor's degree or higher is 25 percent higher than the corresponding ACS

[1] For example, questions exhibiting higher non-response in the Austin survey were modified. A question on a Leaf BEV was added. Experts in the field of travel behavior analysis, vehicle fleet modeling, alternative fuels, energy policy, and transport-survey design were contacted, and their suggestions incorporated.

[2] Major body types were represented by the Honda Civic (Compact car category), Toyota Yaris (Small car), Nissan Maxima (Large car), Lexus ES 350 (Luxury car), Honda Odyssey (Minivan), Ford F-150 (Pickup), and Ford Escape (SUV).

[3] The PHEV's effective fuel economy and purchase price were estimated using information from Kurani et al. (2009), Axsen and Kurani (2008), Markel (2006a), Markel (2006b), and CalCars.com. While the Chevrolet Volt is the first PHEV to hit the U.S. market, Toyota's Prius is already available to respondents, making the Prius PHEV a more realistic choice option for this SP experiment.

[4] There may be greater variation beyond PHEV30, but incorporating those was beyond the scope of this work.

proportion. Each household record was appropriately weighted, to facilitate relatively unbiased model calibration and application.

Table 1: Sample Summary Statistics (Unweighted) versus U.S. Population Average

Variable	Minimum	Maximum	Mean	Std. Deviation	ACS Average
Household variables					
Male indicator	0	1	0.4685	0.4992	0.4931
Age of respondent (years)	20	70	46.49	15.17	47.51
Household (HH) size	1	9	2.463	1.293	2.613
Number of household workers	0	5	1.232	0.8930	1.220
Number of household vehicles	0	5	1.596	0.8227	1.842
Age of oldest household vehicle (years)	0	77	10.22	7.272	-
Annual VMT per household vehicle (miles)	500	60,000	11,183	7,671	-
Annual household income ($/year)	10,000	200,000	59,882	41,045	71,128
Income per HH member	$1,667	$200,000	$31,770	$28,669	-
High income HH indicator (>$75,000/year)	0	1	0.266	0.442	-
Large HH size indicator (5+ members)	0	1	0.082	0.28	-
Location variables					
Job density (# of jobs/sq mile in home ZIP code)	0.053	204,784	1,454	8,525	-
HH density (# of HHs/sq mile in home ZIP code)	0.187	37,341	1,039	2,095	-
Attributes of owned vehicles					
Fuel cost ($/mile)	0.0543	0.1667	0.1057	0.0374	-
Purchase price ($)	15,000	61,500	28,500	12,184	-
Intended transaction decisions in the coming year					
Acquire a vehicle	0	1	0.1775	0.3822	-
Dispose of currently held vehicle	0	1	0.0227	0.149	-
Replace a currently held vehicle	0	1	0.0538	0.2257	-
Do nothing	0	1	0.7317	0.4432	-

Note: All table values come directly from survey responses, except for Fuel cost, which is derived from fuel economies obtained in *Ward's Automotive Yearbook* (2007), and job and household counts by zip code, which come from the U.S. Census Bureau's ZIP Code Business Patterns (2007). The American Community Survey (ACS) average used comes from 2006-2008 data.

Figure 1 presents weighted responses for vehicle choices under different scenarios. Under the trend scenario, the most popular choices were compact cars and SUVs (at 23% and 19% weighted choice shares). Under the gas price scenarios of $5 and $7 per gallon, compact car and HEV received the most votes (22% and 19% at $5 per gallon, respectively, and 23% and 24% at $7 per gallon). Under the final, environmental-costs scenario, the Prius HEV dominated (21.5%), followed by compact cars (20.7%). There was not much variation in the shares of compact, subcompact, and Hummer classes across the four scenarios. Shares of van, SUV, CUV[5], pickup truck, luxury, and large car options decreased under the higher-gas-price scenarios, while popularity of the Smart Car, HEV, and PHEV rose.

Of particular interest is the fact that the environmental-cost scenario's results closely mimic those of the $5/gallon scenario, though the environmental costs (at just 6.4¢ per mile for the pickup option versus 0.5¢/mile for the PHEV) are far lower than the *added* gas costs of a $5/gallon scenario (which range from 14¢/mile for the Hummer to just 0.5¢ for the PHEV [where much of the power is provided by electricity]). It appears that simple labeling or astute advertising may shift perceptions quickly in the direction of a cleaner fleet.

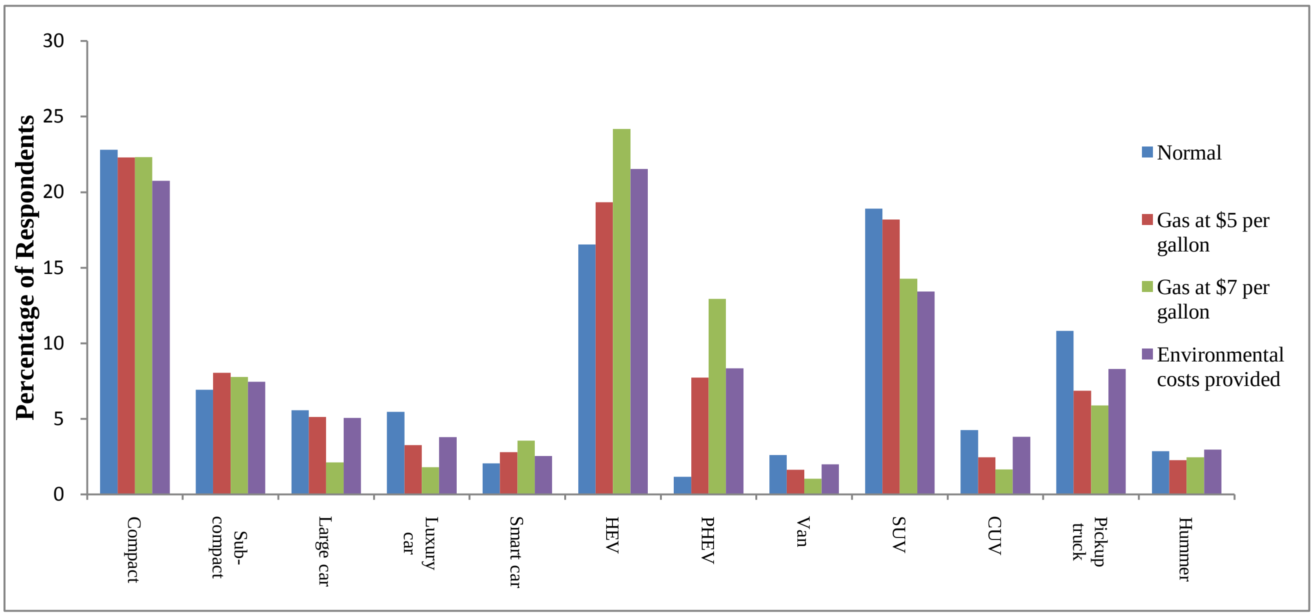

Figure 1: Vehicle Selection under Different Scenarios (Weighted Responses)

Figure 2 summarizes reasons that survey respondents gave for not buying the last two vehicles they had considered purchasing. Unsurprisingly, "too-high purchase price" dominated, followed by "less desired vehicle type", and "too-low fuel economy" – garnering 27.3%, 11.5%, and 8.9% of the (weighted) responses, respectively. While Musti and Kockelman (2010) also found fuel economy to score third highest among Austin respondents' criteria for a coming (not past) vehicle-acquisition event in Austin, and *number one* once all top-three ranks' shares were added, consumers' recognition of fuel economy remains an enigma: Greene's (2010) extensive review reports a lack of consensus among existing studies regarding importance of fuel economy in households' vehicle choice decisions. Of course, the U.S. population does differ from that of Austin (which boasts a highly educated and environmentally conscious population, as noted in Smith et al. [2009]), and used-vehicle purchase prices may much better reflect gas-price conditions (George et al. [1983], Kahn [1986], CBO [2008], Smith et al. [2009], Sallee et al. [2010])

[5] Cross-over utility vehicles (CUVs) borrow features from SUVs but have a car platform for lighter weight and better fuel efficiency.

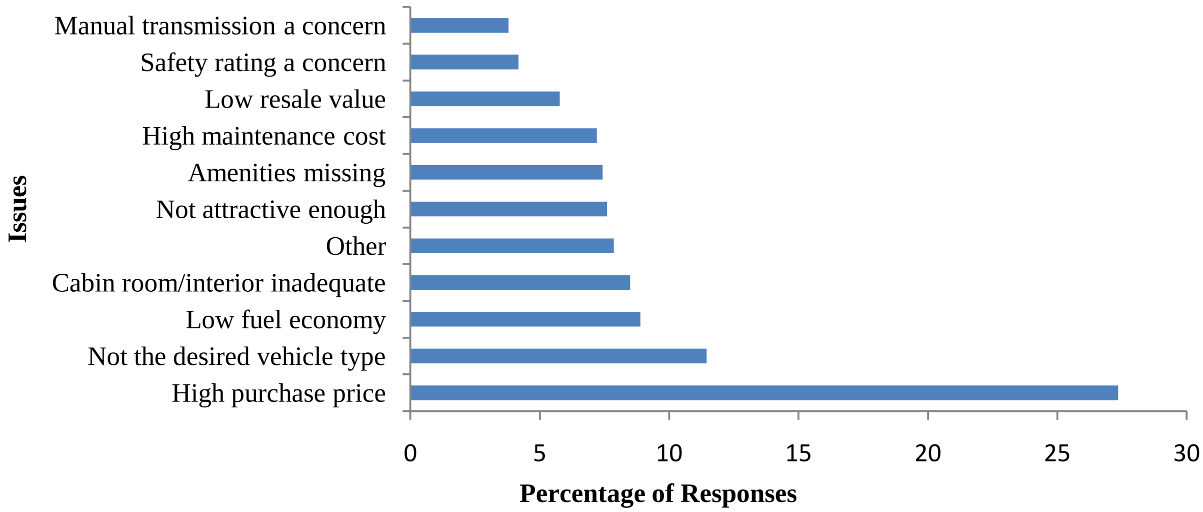

Figure 2: Issues with Vehicles Not Bought During Recent Purchase (Weighted Responses)

Only 29% of the respondents expressed their support for a specific feebate policy (with a fee/rebate of roughly $200 per mpg below/above a 30 mpg pivot point), compared to 63% support in Musti and Kockelman's (2010) Austin survey. But 41.5% (weighted) indicated that they would seriously consider buying a hybrid-electric (HEV) version of a standard vehicle model costing $3,000 more; and 35.5% would consider buying a PHEV at $6,000 more than a comparable gasoline-powered vehicle. Overall, 55.5% reported access to electricity in their garage or a carport near their residential unit.

MODEL CALIBRATION

Models underlying the microsimulation process were estimated using both the stated and revealed preference data sets. Covariate inclusion was decided on the basis of statistical significance (essentially a p-value under 0.10) following a process of stepwise addition and deletion. A model for numbers of vehicles owned was not required since this information came from survey data (used for constructing base population). Details of model calibration and application results are provided below.

Vehicle Ownership Based on Revealed Preferences

Survey respondents' current vehicle holdings were grouped into nine vehicle types (choice set): CUV, large car, luxury car, midsize car, pickup truck, compact, subcompact, SUV, and van. MNL models controlled for demographic attributes, neighborhood densities, and generic attributes of the 9 alternatives (i.e., fuel cost and purchase price). Table 2 presents the weighted-MNL coefficient estimates of the 1,778 vehicles (from the 1,079-household data set). Among these, 18% are mid-size cars, 16.5% are compact cars, 16% are pickup trucks, 15.4% are SUVs, and the remaining 34.1% are comprised of CUVs, luxury cars, large cars, and vans.

The coefficients corresponding to fuel cost and vehicle purchase price are statistically significant and intuitive. Households with many vehicles are relatively likely to own a compact car. Those of higher income are likely to own a compact car and/or SUV. Households with more workers are less likely to hold a CUV or compact car, and larger households prefer mid-size cars, pickup trucks, SUVs, and vans, probably due to seating capacity and storage space needs. Older male respondents have a higher tendency to own CUVs, ceteris paribus.

Table 2: Vehicle-Type Ownership Model Parameter Estimates (Weighted MNL)

Variable	**Coefficient**	**T-stat**
CUV	-1.690	-3.64
Large car	-0.7813	-7.05
Subcompact	-1.333	-8.18
Fuel cost (dollars per mile)	-4.448	-2.76
Purchase price (dollars) x 10^{-5}	-3.392	-7.36
Male respondent x CUV	0.6311	2.92
Respondent age x CUV	0.0186	2.44
Number of workers x (CUV, Compact)	-0.3848	-5.51
Large household size (>4) indicator x (Midsize car, Pickup truck, Compact, SUV, Van)	0.9601	3.89
Household income x (Compact, SUV)	4.17E-06	5.02
Number of vehicles in household x Compact	0.1112	1.83
Job density x (CUV, Subcompact, Van)	-8.85E-05	-1.97
Household density x Van	-2.41E-04	-2.49
Household density x (Midsize car, Pickup truck, Compact, SUV)	1.06E-04	2.24
Log Likelihood at Constants	-3682.16	
Log Likelihood at Convergence	-3673.80	
Pseudo R^2	0.0596	
Number of Observations	1778	

Note: Luxury car is the base alternative.

Vehicle Ownership based on Stated Preferences

The online survey offers three special vehicle type categories: a Prius HEV, a Prius PHEV30 (which does not yet exist), and a Mercedes Smart Car. Top choices of the 1,098 respondents were the compact car (22.8%, weighted), SUV (19%), HEV (16.5%), and pickup truck (10.8%). The remaining 30.9% elected a subcompact car, luxury car, large car, Hummer, van, Smart Car, or PHEV. MNL estimates for SP vehicle choice model are presented in Table 3.

Table 3: SP Vehicle Type Choice Parameter Estimates (Weighted MNL)

Variable	**Coefficient**	**T-stat**	**Re-estimated ASCs**
Subcompact	-0.6494	-3.31	-0.9147
Compact	-	-	-1.210
Large	-	-	-1.165
Luxury	-	-	-0.4314

Smart Car	-	-	-3.033
HEV	-	-	-1.878
PHEV	-	-	-0.4345
CUV	-	-	0.6566
SUV	-	-	-1.452
Pickup	-	-	-0.3442
Hummer	-	-	-3.058
Fuel cost (dollars per mile)	-5.206	-2.77	-
Purchase Price (dollars) x 10^{-5}	-4.004	-5.61	-
Male respondent x (Hummer, Pickup truck)	1.208	6.49	-
Male respondent x (Large car, Luxury car)	0.4621	2.92	-
Male respondent x SUV	0.3287	2.2	-
Age of respondent x (HEV, Subcompact, SUV)	0.01122	5.09	-
Household size x Smart Car	-0.5978	-4.63	-
Large household indicator (>4) x Compact	0.6849	3.02	-
Large household indicator (>4) x Hummer	2.24	5.71	-
Number of workers x PHEV	-1.097	-4.01	-
Number of workers x Pickup truck	0.3651	3.91	-
Number of household vehicles x (Compact, CUV, HEV, Large car, Luxury car, SUV)	0.2331	3.18	-
Household Income ($/Year) x Compact	1.03E-05	7.42	-
Household Income ($/Year) x SUV	4.15E-06	2.45	-
High income indicator (>$75k) x Luxury	0.3962	1.49	-
Income per member (dollars) x Pickup truck	6.02E-06	2.01	-
Job density (jobs per sq mile) x Compact	1.23E-04	4.14	-
Job density (jobs per sq mile) x Luxury car	7.20E-05	1.58	-
Household density (HHs per sq mile) x (PHEV, HEV)	1.40E-04	3.47	-
Log likelihood at constants	-2351.08		
Log likelihood at convergence	-2342.75		
Pseudo R^2	0.1517		
Number of observations	1,098		

Note: Van is the base alternative.

Coefficients on fuel cost and purchase price came out to be statistically significant, as expected. Results suggest that households with many vehicles are likely to select a CUV, HEV, large car, SUV, or a luxury car. Respondents from high-income households appear to prefer compacts, CUVs, HEVs, large cars, luxury cars, and SUVs, while those with higher incomes per household member seem to prefer a Smart Car, ceteris paribus. Larger households are more likely to choose a compact or Hummer but are less likely to select a Smart Car, due to capacity considerations. Results also suggest that older respondents are more likely to own an HEV, subcompact car, or SUV, with male respondents displaying more of a preference for Hummers, pickup trucks, large cars, luxury cars, and SUVs.

The predicted shares of vehicles from this model come from a relatively small data set and so cannot closely match recent U.S. sales patterns (according to Ward's Automotive Yearbook for 2010 [which provides 2008 and 2009 model year sales numbers]. The purchase model over-predicted sales shares of HEVs, Compact cars, and SUVs and under-predicted Subcompact, CUV, and Pickup truck shares. Therefore, 11 alternative specific constants (ASCs) were adjusted to match the predicted sales pattern to the actual US sales pattern in the base year (as described in Train [2009]). These re-estimated ASCs are presented in Table 3's third column.

Vehicle Transactions Model

Survey respondents were given four choices for their intended transactions in the coming year: acquire a vehicle, dispose of one, replace a vehicle, or do nothing. Out of the 1,103 respondents, 18% (weighted) indicated their intent to acquire an added vehicle in the coming year, 2.3% (weighted) felt they were likely to simply dispose of an existing vehicle, 5.5% (weighted) expected to replace a vehicle, and the remaining 74.2% planned to maintain their current fleet. Table 4 presents all parameter estimates. The ASCs were adjusted to match the vehicle-count growth rates in the US[6]. These adjusted ASCs are presented in Table 4's final column.

Table 4: Annual Household Transactions Model Estimates (Weighted MNL)

Variable	Coefficient	T-stat	Re-estimated ASCs
Acquire (indicator)	-	-	-1.022
Dispose (indicator)	-3.981	-16.78	-4.042
Replace (indicator)	-2.557	-13.67	-2.660
Male respondent x Replace	-0.7601	-2.69	-
Age of respondent x Acquire	-0.0335	-8.82	-
Number of children x Replace	0.4153	3.62	-
Number of workers x Acquire	0.3019	3.07	-
Number of vehicles in the household x Acquire	-0.5748	-4.37	-
Maximum age of vehicle in household x (Acquire, Dispose)	0.0551	5.35	-
Low income household (<$30k) x Acquire	-0.5231	-1.88	-
Household density x Dispose	7.81-05	1.27	-
Log Likelihood at Constants	-921.0		
Log Likelihood at Convergence	-807.2		
Pseudo R^2	0.4721		
Number of households	1103		

Note: Do Nothing is the base alternative.

Results are quite intuitive, suggesting, for example, that households with many vehicles are less likely to acquire a new vehicle to maintain their current fleet. Households with many workers are more likely to acquire another vehicle in the coming year, ceteris paribus. Older respondents

[6] Vehicle growth rates were obtained from Bureau of Transportation Statistics, for the years 2000 through 2008. (http://www.bts.gov/publications/national_transportation_statistics/html/table_01_11.html)

appear less likely to acquire, and male respondents are less likely to replace. Higher household density settings are associated with greater disposal likelihood. Low-income household seem less likely to acquire a new vehicle.

Vehicle Usage and GHG Emissions Estimates

The annual VMT estimates collected in the survey are simply respondent estimates of a year's worth of mileage accumulation on each vehicle owned (rather than using odometer readings, for example) and did not give robust results. Therefore, the vehicle usage model was estimated on the extensive (n=196,606 vehicles) 2009 National Household Travel Survey (NHTS) sample. The NHTS sample reported an average yearly VMT of 10,089 miles per vehicle (with σ=9,244 miles). Table 5 presents the parameter estimates of this least-squares regression, with coefficients for variables of fuel cost and population density added (based on published estimates) to ensure more appropriate model sensitivities.

Table 5: Annual VMT per NHTS 2009 Vehicle (Unweighted)

Variable	Coefficient	T-Stat	Mean Elasticity
Constant	2.411	77.1	-
Pickup	-2.76E-02	-4.36	-
SUV	0.0987	14.92	-
Van	0.1108	12.02	-
Fuel cost (Dollars/mile)	-1.711	-	-0.25
HH density (#HHs/Sq mile)	-8.08E-05	-	-0.08
Household size	0.0644	28.12	0.1678
Number of workers in household	0.2011	64.12	0.2372
Number of vehicles in household	-0.1279	-60.53	-0.3389
Age of vehicle (years)	-0.0636	-184.43	-0.568
Household income (dollars)	3.17E-06	43.00	0.2212
R^2	0.2373		
Adjusted R^2	0.2373		
Number of observations	199,606		

Note: Dependent variable is Ln(VMT/1000). Elasticities were computed for each household and then averaged to provide mean sample elasticities.

Results are as expected, with vehicle age having negative impact on annual VMT – and with vehicle age enjoying the greatest practical significance. Household income, size, and number of workers also have statistically significant effects, but without as great practical significance as vehicle age. Fuel cost and residential density were the key variables missing from this model (due to a lack of detailed fuel-price and home-location information in the data set [and presumably little variability, across the U.S.]). These variables have important impacts on VMT and have been studied extensively. (See, for example, Haughton and Srakar [1996], Greene et al. [1999], Small and Dender [2007], Hughes, Knittel and Sperling [2008], Fang [2008], Brownstone and Golob [2009], National Research Council [2009], Musti and Kockelman

[2010].) Table 5's two added coefficients achieve elasticity values obtained in previous studies, with the model's Constant term then adjusted to equate the average of predicted and observed VMT values.

Table 5's parameters were used to predict annual VMT at the final year of simulation for each household in the 2035 synthetic population (having grown to a total of 66,367 households). These VMTs were translated into GHG emissions using EPA's (2007) standard (well-to-wheels) conversion value (of 25.4 lbs of CO_2e per gallon of gasoline) and EIA's (2000) 1.34 lbs of CO_2e per kWh of electricity generated (U.S. average). The share of PHEV miles on electric power were estimated using utility factor curves (as found in Markel and Simpson (2006), Gonder et al. (2009), Simpson (2006), and Kromer and Haywood (2007)).

In applying the calibrated models, the simulation anticipates each household's vehicle holding (and use) decisions on a yearly basis, by relying on Monte Carlo draws. In the case of a "buy/acquire" decision, the SP vehicle choice model was used to determine the type of vehicle acquired by the household. For "disposal" decisions, the household vehicle with the lowest systemic utility was removed. "Replace" decisions relied on both these actions. The following section describes the results of these models' applications, in the simulation system.

RESULTS OF FLEET SIMULATION

Figure 3 provides the overall microsimulation framework. The number of households is predicted to grow by 32.7% over the 25-year simulation period, with population rising by 27%and household size falling by 4.07%. Average household income is expected to increase at a steady annual rate of 0.82%. These results are close to demographic trends observed via the U.S. National Household Travel Survey (Hu and Reuscher 2004).

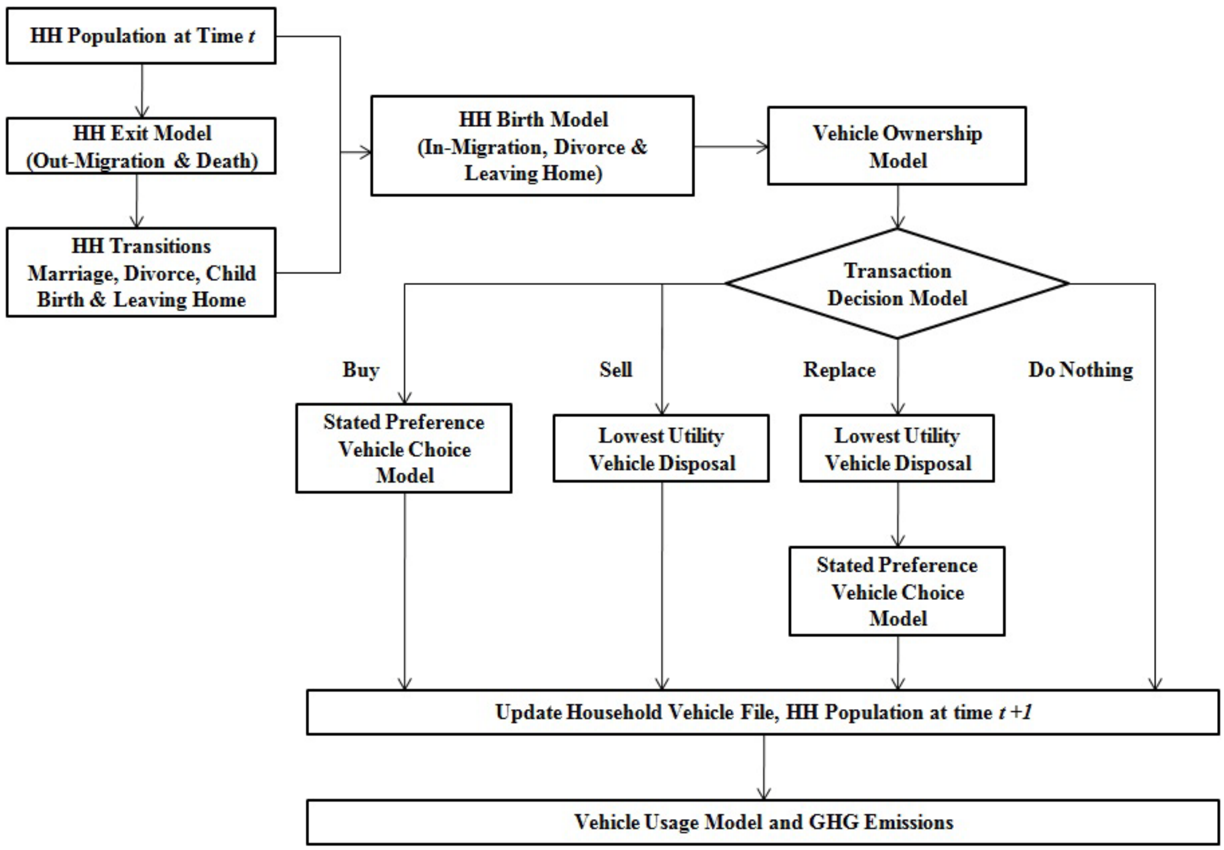

Figure 3: Modeling Framework

The synthetic U.S. households' vehicle fleet was evolved under several scenarios, including a GASPRICE$7 scenario (where gas prices were raised to $7 per gallon), a LOWPRICE scenario (where the base price of the PHEV option fell by $4,100, to $ 28,900, which is still $3,900 more than a comparable ICE), a FEEBATE scenarios (rebates to vehicles with over-30 mpg, and fees otherwise [at a rate of roughly $200 per mpg]), a HI-DENSITY scenario (where all household and job densities were quadrupled), a TREND (or base-case) scenario, and combination of FEEBATE and LOWPRICE scenarios with gas prices raised to $5 per gallon). Results of all these scenarios are presented below.

Fleet Composition

Table 6 summarizes the fleet composition predictions for the final simulation year (2035). Under the TREND scenario, HEV market share was estimated to hit 5.68% by 2035, PHEV share came in at just 1.91% and a (standard) Smart Car under 1%. Interestingly, more than 75% of the HEV or PHEV are held by households with 3 or fewer vehicles by 2035.

Under the GASPRICE$7 scenario, market shares of HEVs, PHEVs, and Smart Cars rose to 11.08%, 3.45%, and 0.30%, respectively, as shares in Pickup trucks, SUVs, CUVs, and Vans fell. This scenario predicted the highest market share (14.83%) for PHEVs, HEVs and Smart car, across the seven scenarios examined here.

The LOWPRICE scenario did not predict any significant fleet share changes, versus TREND, other than increasing the market shares of PHEVs slightly (to 2.33%, from 1.91% in the TREND scenario). Households with three or fewer vehicles were predicted to own the majority (77%) of the household fleets' PHEVs and HEVs. The majority (84%) of PHEVs are simulated to be owned by households with 3 or fewer members.

Feebates prompted a shift toward more fuel efficient vehicles, with the combined HEV/PHEV market share predicted to hit 9.2% by 2035. Market shares of Pickup trucks and Vans fell, while other shares moved negligibly. This particular feebate policy resulted in fee collections dramatically exceeding rebates, by a ratio of 4.91 (fees collected to rebates distributed) in year 2015, falling to 4.39 and 4.43 by 2025 and 2035, with 70% of rebates going toward HEV purchases on average. The ratio of fees to revenues is high, in part, since just three of the vehicle alternatives (just the HEV, PHEV, and Smart Car alternatives), among the 12 total, enjoyed fuel economy values above the policy's pivot point threshold. Of course, the model also ignores the technological improvements that may emerge over time, due to gas price changes, technology innovations, and regulatory shifts that can impact vehicle purchase and use prices, vehicle alternatives, and users' choices.

Inclusion of a $5 per gallon gas price assumption in the FEEBATE scenario increased the shift towards fuel efficient vehicles and produced higher market shares for HEVs, PHEVs, and Smart cars. The LOWPRICE scenario along with $5 per gallon gas price, as expected, increased the share of PHEVs (from 1.91% in TREND to 3.31%).

Finally, the HI-DENSITY scenario predicted average vehicle ownership levels to fall to 1.98 vehicles per household (from 2.10 under TREND). Off course, vehicle ownership levels are not expected to be this high under both scenarios, given the current growth rate of registered vehicles in U.S. (1.35% between 2003 and 2008[7]) and household growth rate. Under this scenario the share of compact cars, PHEVs, and HEVs increased noticeably, while those of CUVs, SUVs, and Pickup trucks fell.

To summarize, while 25 years is a long period of time, and generally enough to flush a personal-vehicle fleet almost entirely (thanks to an average U.S. light-duty-vehicle lifetime of roughly 15 years), the various, relatively reasonable policy scenarios tested here appear to have relatively little impact on most vehicle sales shares, with the exception of HEV purchases under a $7 gas-price and high density scenario. More aggressive action appears needed. For example, the U.S.'s current policy of a $7.5k rebate for the first 200,000 PHEV and BEV sales could be tested, more policies could be layered in the scenarios, including more aggressive feebate and density scenarios. It would also be interesting to recognize California's decision to allow eligible low emission vehicles[8] into that state's high-occupancy-vehicle (HOV) lanes, and localities plans' for preferential PEV parking spaces, though the analyst would have to guess at the base-utility impacts of such a policy and of a BEV purchase, since these scenarios were not evaluated in the online survey's design.

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[7] Bureau of Transportation Statistics (BTS), Available at : http://www.bts.gov/publications/national_transportation_statistics/html/table_01_11.html

[8] Details of eligible vehicles can be found at: http://www.arb.ca.gov/msprog/carpool/carpool.htm

Table 6: Vehicle Fleet Composition Predictions (Counts and Percentages) for the Year 2035

	Base Year (2010)		Base Scenario (TREND)		Gas at $7/gal (GASPRICE$7)		Low PHEV Price (LOWPRICE)		Feebate Policy (FEEBATE)		Quadrupled Job & Household Density (HI-DENSITY)		Low PHEV Price + Gas at $5/gal		Feebate + Gas at $5/gal	
Subcompact	6291	7.98%	8,457	6.06%	12,847	9.26%	8,540	6.10%	8,920	6.46%	7,493	5.68%	10,850	7.80%	11,569	8.38%
Compact	13,115	16.64	33,368	23.91	34,478	24.86	33,567	23.98	33,660	24.38	36,603	27.74	33,962	24.43	34,614	25.07
Mid-size	14,768	18.73	10,513	7.53	9,987	7.20	10,462	7.48	10,543	7.64	9,387	7.11	10,319	7.42	10,180	7.37
Large	3,437	4.36	3,473	2.49	3,055	2.20	3,401	2.43	3,373	2.44	3,166	2.40	3,194	2.30	2,996	2.17
Luxury	6,878	8.73	9,711	6.96	8,095	5.84	9,545	6.82	9,097	6.59	9,328	7.07	8,644	6.22	8,140	5.90
Smart Car	-	-	149	0.11	411	0.30	187	0.13	217	0.16	146	0.11	235	0.17	328	0.24
HEV	-	-	7,934	5.68	15,361	11.08	7,980	5.70	9,496	6.88	9,051	6.86	11,573	8.33	13,690	9.92
PHEV	-	-	2,671	1.91	4,784	3.45	3,258	2.33	3,201	2.32	3,119	2.36	4,602	3.31	4,415	3.20
CUV	3,936	4.99	13,084	9.37	11,428	8.24	13,019	9.30	12,130	8.79	10,911	8.27	12,090	8.70	11,127	8.06
SUV	12,273	15.57	18,330	13.13	14,882	10.73	18,455	13.19	17,856	12.93	15,963	12.10	16,557	11.91	15,773	11.43
Pickup	11,524	14.62	23,711	16.99	17,377	12.53	23,370	16.70	21,591	15.64	21,037	15.94	19,860	14.29	18,312	13.27
Van	6,607	8.38	8,093	5.80	5,902	4.26	8,083	5.78	7,884	5.71	5,658	4.29	7,055	5.08	6,812	4.93
Hummer	-	-	87	0.06	92	0.07	86	0.06	93	0.07	88	0.07	73	0.05	88	0.06
Total #Vehs.	78,829		139,581		138,699		139,953		138,061		131,950		139,014		138,044	
Avg. #Vehicles per Household	1.59 Vehs/HH		2.10		2.09		2.11		2.08		1.98		2.10		2.08	

Note: These numbers are for the simulation's final-year synthetic population, of 66,367 households (representing a total U.S. population of 534 million

Vehicle Miles Travelled and GHG Emissions

Table 7 presents Year 2010 and 2035 VMT and GHG-related emissions estimates across scenarios. NOx and VOC comprise 5 to 6% of total vehicle GHG emissions, while CO2 emissions account for the other 94 to 95% (EPA, 2005). Under the TREND scenario, U.S. household VMT is expected to rise by 65.4% versus the 2010 base year. GASPRICE$7As expected, all scenarios with gas price increases produce a drop in total VMT, while the LOWPRICE and FEEBATE scenarios produce a rise thanks to lower vehicle operating costs. Emissions under all increased gas price scenarios are expected to fall, largely following the VMT trends. And, even though VMT is predicted to rise under the two FEEBATE scenarios, the emissions fall, thanks to a higher share of HEVs and PHEVs in the fleet. Finally, both VMT and emissions are simulated to fall under the HIDENSITY scenario, due to relatively low vehicle ownership.

While different vehicle types enjoy very different fuel economies[9], the CO2e values largely follow the VMT shifts predicted. Clearly, far more dramatic fleet shifts (and scenarios) are needed if the U.S. is to reduce the GHG contributions of its personal-vehicle fleet over time.

[9] Fuel Economy (mpg) assumptions: Compact (20.65), Subcompact (26.6), Large(17.57), Luxury (18.61), Smart (36), HEV (46), PHEV (45), CUV (18.08), SUV (15.1), Pickup (14.67), Van (15.18), Hummer (16), midsize (19)

Table 7: VMT and CO_2e Estimates (Total and per Vehicle) in 2035

	Base Year (2010)	**Base Scenario (TREND)**	**Gas at $7/gal (GASPRICE$7)**	**Low PHEV Price (LOWPRICE)**	**Feebate Policy (FEEBATE)**	**High Job & Household Density (HI-DENSITY)**	**Feebate+Gas at $5/gal**	**Low PHEV Price + Gas at $5/gal**
Total VMT (million miles)	1,210	2001	1,478	2,114	2,188	1,736	1,796	1,727
% change from TREND			-26.14%	+5.65%	+9.35%	-13.24%	-10.25%	-13.69%
Total CO_2e emissions (million pounds)	1,464	2,358	1,460	2,363	2,226	1,918	1,713	1,804
% change from TREND			-38.08%	+0.21%	-5.59%%	-18.66%	-27.35%	-23.49%

Note: These numbers are for the final year (2035) synthetic population, of 66,367 households

SUMMARY & CONCLUSIONS

This work presented a microsimulation framework to evolve a synthetic population's personal vehicle fleet in order to represent the U.S. population over a 25-year period (2010 through 2035). Data were collected via an online survey eliciting information on respondents' current vehicle holding and use, purchase decisions, and intended vehicle choice under different policy scenarios. Revealed and stated preference vehicle-choice models were estimated, along with transaction and use models.

Future market shares of PHEVs, HEVs, and vehicles like the Smart Cars are of interest to manufacturers, policy makers, and many others. Predicted shares vary by scenario, with 14.8% serving as their highest (total) predicted share by 2035, under the GASPRICE$7 ($7 per gallon) scenario, with HEVs clearly dominating this share (with a predicted 11.1% share). While 14.8% is clearly higher than the TREND's 7.7% share of these three relatively efficient vehicle types, the GASPRICE$7 scenario's reductions in fleetwide CO_2e emissions (38.1%) come mainly from lower VMT. Similar trends were also predicted for other gas price scenarios..
The LOWPRICE scenario's results suggest a slight increase in the PHEV share (as compared to TREND), with almost no change in VMT and GHG emissions. Under the FEEBATE policy, PHEV shares rise, but so does VMT (very slightly), owing to a rebound effect (see, e.g., Small and van Dender [2007]), but CO_2e emissions are forecast to fall by 5.59%, thanks to higher shares of fuel efficient vehicles. Unfortunately, such numbers are far less than desired by policymakers and nations hoping to moderate climate change and other environmental implications of oil dependence, while addressing energy security, continuing trade deficits, high military costs, and other concerns (see, e.g., Greene 2010, Sioshanshi and Denholm 2008, Thompson et al. 2009).

While the FEEBATE scenario targets purchases of fuel-efficient vehicles, the series of behavioral models used here suggests that a gas price of $7 per gallon will have more of an impact on ownership shares, as well as producing lower CO2e emissions, across scenarios. While only a 29% population-weighted-share of respondents expressed support for a feebate policy (versus Austin's 63% [Musti and Kockelman 2010]), and only 35% (weighted) intend to buy a PHEV if it costs just $6,000 more than its gasoline counterparts (versus Austin's 56%), greater support for such policies and more widespread use may emerge if marketing is strategic and pronounced (e.g., alerting buyers to gasoline expenditures and external costs of their vehicle's emissions, versus other vehicle options), government incentives remain in place longer (e.g., the $7,500 PEV rebate past the first million PEV sales), charging infrastructure is well advertised, HOV-lane priorities and other perks are provided PEV owners, power pricing levels facilitate vehicle-to-grid interactions, battery prices fall, and so forth. Perhaps feebate and such policy will trigger technological improvements and in turn will affect the vehicle-mix shift (Bunch 2010). Nonetheless, this work helps in anticipating how vehicle ownership and usage patterns and associated emissions might change under different policies and contexts. The methods and tools used in this study provide a framework for comparing various policy scenarios. This work also helps highlight the impacts of various directions consumers may head with such vehicles, and more scenarios may be tested. These include the addition of battery-electric vehicle and plug-in SUV and large-car options, inclusion of a fuel-cost variable in the vehicle use (VMT) model, and the impacts of stricter CAFE standards over time.

In addition, it would be meaningful to microsimulate the used-car market (and its pricing dynamics, as in Selby and Kockelman [2010]), particularly since 40% (weighted) of survey respondents expected to buy a used car next. A model reflecting unexpected vehicle loss (due to thefts, malfunctions, and crashes) and delays in actual (versus intended) acquisitions should also facilitate more realism. Estimation and application of simultaneous vehicle-choice-and-use models (as in Mannering and Winston [1985]) may also help, by more directly linking ownership and operating expenses. Finally, owners may exhibit greater variation in their vehicles' annual use, by vehicle type and in response to other attributes (observed and latent) than our model estimates suggest; moreover, range-limited BEVs may shape VMT choices. Incorporating such details may improve VMT and CO2e estimates. Of course, many such enhancements point to a need for further data collection, to better emerging vehicle make-and-model options, technologies, and traveler behaviors. The hope is that very solid markets exist, both in the U.S. and abroad, for energy- and carbon-saving vehicles, with smaller environmental and physical footprints. Models like those used here are one tool toward finding policies and vehicle designs that enable communities to better evaluate their options and achieve their aspirations.

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