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ABSTRACT

Toyota's introduction of a hybrid electric vehicle (HEV) named "Prius" in Japan and Honda's proposed introduction of an HEV in the United States have generated considerable interest in the long-term viability of such fuel-efficient vehicles. A performance and cost projection model developed entirely at Argonne National Laboratory (ANL) is used here to estimate costs. ANL staff developed fuel economy estimates by extending conventional vehicle (CV) modeling done primarily under the National Cooperative Highway Research Program. Together, these estimates are employed to analyze dollar costs vs. benefits of two of many possible HEV technologies. We project incremental costs and fuel savings for a Prius-type low-performance hybrid (14.3 seconds zero to 60 mph acceleration, Z60 time) and a higher-performance "mild" hybrid vehicle, or MHV (11 seconds Z60 time). Each HEV is compared to a U.S. Toyota Corolla with automatic transmission (11 seconds Z60 time). The base incremental retail price range, projected a decade hence, is $3,200-$3,750, before considering battery replacement cost. Historical data are analyzed to evaluate the effect of fuel price on consumer preferences for vehicle fuel economy, performance, and size. The relationship between fuel price, the level of change in fuel price, and consumer attitude toward higher fuel efficiency is also evaluated. A recent survey on the value of higher fuel efficiency is presented and U.S. commercial viability of the hybrids is evaluated using discount rates of 20% and 8%. Our analysis, with our current HEV cost estimates and current fuel savings estimates, implies that the U.S. market for such HEVs would be quite limited.

I. INTRODUCTION

This paper examines the importance of fuel economy in the choice of vehicle by consumers, and then some implications for the potential market for two specific types of hybrid vehicles in one vehicle size class.

In the first section, emphasis is placed on the willingness on the part of households to pay extra to purchase a more fuel-efficient vehicle (FEV). Two questions are addressed by use of survey information. First, what subset of consumers appears to place a higher value on fuel economy? Second, how does the valuation of fuel economy change with gasoline prices?

The second section looks at a particular type of FEV, the class of hybrid electric vehicle (HEV) being produced by Toyota (Toyota, 1997 and Hermance, 1998, 1999). This paper examines the nature of the price vs. fuel economy trade-off. Of several fuel economy estimates examined, one set relies on extension of CV models developed by staff of the University of California at Riverside (UCR) (An, Barth, and Scora, 1997; An and Barth, 1998). Feng An has extended this model to analyze HEVs for Argonne National Laboratory (ANL) (An, Stodolsky, and Santini, 1999). Fuel economy estimates used here have also been calibrated against estimates by the ADVISOR vehicle simulation model developed at the National Renewable Energy Laboratory (NREL) (Wipke et al, 1998; Wipke, Cuddy, and Burch, 1999). Indirectly, through analysis adapted from other references, the paper also draws on test data for the Prius hybrid vehicle (Hermance, 1998, 1999, Hellman, Peralta, and Piotrowsky, 1998). For cost estimation, an as-yet-undocumented model developed at Argonne – the Hybrid Electric Vehicle Component Sizing and Cost model (HEVCOST) – is used, together with information developed by K.G. Duleep (1998) that provides a starting point.

HEVs are difficult to characterize because they can have so many formulations (grid or non-grid, series or parallel, mild or full, etc.). To this we can add a usual distinction among all motor vehicles concerning high vs. low performance – as measured by ability to accelerate. The preliminary evidence is that performance increases in a hybrid vehicle have far less detrimental effect on fuel economy than those in a conventional gasoline vehicle (An, Stodolsky, and Santini, 1999; Santini et al., 1999). Grid or non-grid refers to whether or not the hybrid is designed to plug into the electric grid and use that electric power in place of gasoline. The Prius itself, defined as part series and part parallel, is mostly parallel and is grid-independent. As An, Stodolsky, and Santini (1999) defined the terms, the Prius is a full hybrid. One with a proportionally smaller motor and battery pack (and larger engine) is called a mild hybrid vehicle (MHV). An, Stodolsky, and Santini characterized the performance and fuel economy attributes of five variants of hybrids, all based on an original vehicle simulation model calibrated to the Prius. We examine only two of these five, comparing them with a recent model year U.S. Toyota Corolla with automatic transmission. The Prius has a continuously variable transmission, which is most appropriately compared with an automatic transmission in a conventional vehicle.

The third section of this paper combines the benefits of fuel economy and the potential cost of variants of the Prius-type HEVs to estimate potential market shares. We find only limited potential for HEVs in the small car segment of the household vehicle market, unless gasoline prices rise significantly. We have not examined "hybridization" in vehicles (e.g., sport utility vehicles) that are presently not fuel-efficient in order to convert them to FEVs. In the near term, for the subcompact and minicompact vehicles to be offered by Toyota and Honda, respectively, we believe retail prices that cover the costs of manufacture are likely to be higher than U.S. new vehicle buyers are willing to pay. This is consistent with the announced marketing strategy of selling thousands to tens of thousands of these vehicles in the U.S., probably to customers with an altruistic environmental sensibility.

In the short run, manufacturers can choose to sell new-technology vehicles (such as HEVs) below cost. If Toyota and Honda expect that conditions favorable to the hybrid vehicle market have a reasonable probability of emerging in the next several years, their early U.S. sales at a loss could be rewarded. The technical success of the Toyota and Honda hybrids sold in the early part of the decade might serve to establish a customer base for later sales. By introducing and selling hybrids now, they may (1) build up experience and some economies of scale for HEV production; (2) establish a "green" image as providers of low-GHG-emissions vehicles; and (3) adapt HEVs sold in the U.S. market to its characteristics, through customer feedback.

In the long run, if manufacturers stick with this technology, vehicle prices will be set at some increment over the cost to earn profits on HEVs. The cost to produce an HEV depends on many factors: battery type, acceleration capability, hill climbing ability, heating and air-conditioning performance, and interior space for passengers and luggage (all-electric range capability can be a major factor, but the HEVs examined here have none). Separately, we examined the marketability of Prius-type hybrids in Japan, the U.S., and Europe, estimating net benefits for a switch from a conventional gasoline vehicle to a Prius-type HEV in Japan and, under some conditions, Germany (Santini and Vyas, 1999). However, we have not examined whether net benefits would be estimated in those locations when such an HEV is compared to a diesel.

In the United States, the EPA has proposed "Tier II" emissions standards, which will require average nitrogen oxides (NO_x) emissions of 0.07 g/mi from passenger cars by 2004. The NO_x standards presently applicable through 2003 are 0.4 g/mi for gasoline passenger cars and 1.0 g/mi for diesel passenger cars at 50,000 miles (0.6 and 1.25, respectively, at 100,000 miles) (AAMA, 1997, p. 84). A new Prius has been tested by EPA (Hellman, Peralta, and Piotrowsky), on a vehicle dynamometer, at 0.05 g/mi (many new gasoline cars also are certified on vehicle dynamometers to emit less than 0.07 g/mi). The evidence is that the HEV already can meet the Tier II standard, but three diesel passenger cars cited by Hellman, Peralta, and Piotrowsky had NO_x emissions from 0.59 to 0.69 g/mi. The challenge for the diesel to meet potentially strict new NO_x emissions standards is probably considerable, and the "next" FEV passenger car technology to be considered in the U.S. may have to be the HEV rather than the diesel. In any case, the yet-to-be-determined emission control costs imposed on the diesel will make the HEV vs. diesel comparison much more favorable for the HEV than it would otherwise be.

Focusing on the Prius as a baseline, we examine the following:

1. One battery type – nickel metal hydride
2. A vehicle with no all-electric range, but normal range on gasoline
3. Vehicles with the slow acceleration of the present Prius (14 seconds, 0-60) and average acceleration (11 seconds)
4. An HEV with less hill-climbing capability than a conventional gasoline vehicle, with the same 0-60 time
5. Normal heating and air-conditioning performance

6. An HEV with a slightly lower ratio of trunk volume to passenger compartment volume than a competing gasoline vehicle. (The Prius is classed as a subcompact by EPA, based on trunk and passenger compartment volume. We believe that the passenger compartment volume is similar to that of a compact car).

The values that consumers place on all these vehicle attributes are important in determining how popular a specific HEV might be in the household marketplace. This paper does not deal with the potential for HEVs in the commercial fleet or in government use.

II. WHY DO CONSUMERS BUY MORE FUEL-EFFICIENT VEHICLES?

The straightforward answer is that consumers will pay more for a vehicle that has greater fuel economy than the base vehicle under consideration, all else being equal. Engineering economics teaches us to compare the increment in cost for the more expensive vehicle to the net present value (NPV) of the decrements in fuel expense for that vehicle. In the case of the hybrid vehicle, the battery must be replaced during the vehicle's life, so the NPV of battery replacements must also be considered.

Greene (1998), in discussing the merits of fuel economy standards, has noted that this logic does not seem to work. His argument applies to conventional gasoline vehicles, which may have a few mpg of difference at best. At present fuel prices, the NPV of fuel savings for the vehicles compared are on the order of the cost of a different set of tires, or a hubcap upgrade. This applies to NPV calculations for the average consumer; later, we will examine the implications of looking at extraordinary consumers who drive a lot. For the average consumer, Greene's point is well taken. For most people evaluating the purchase of a new vehicle, the value of potentially purchasable fuel economy improvements is "in the noise." Fuel economy is often packaged with other attributes, rather than offered as a straightforward option that can be selected by itself. In the case of the hybrid, however, the fact that the vehicle is under consideration for its fuel economy benefits will be clear. Unlike competing conventional vehicles of the same size and performance, the NPV of fuel savings from purchasing a hybrid is likely to be large, as are the incremental costs of the vehicle. So, the decision process will definitely be focused on costs and benefits of fuel economy when consumers compare hybrid vehicles to conventional vehicles of similar size and performance.

Importance of Fuel Economy, Performance, and Vehicle Size Varies with Fuel Prices

Fuel Economy

The number of individuals likely to make the trade-off between fuel economy and vehicle cost paramount will likely vary with the price of fuel. As prices rise, consumers can be expected to spend more time evaluating the fuel economy of the vehicles they buy.

By examining a series of surveys over the years, we developed a record of the percentage of respondents who placed fuel economy at the top of a list of vehicle attributes considered in the purchase decision. For a total of eight survey years, over the interval 1980 to 1998, we obtained the percentage of respondents who indicated that fuel economy was the most important (among five) vehicle attribute affecting the purchase decision. We statistically estimated these results as a function of both the level and rate of change of real gasoline prices. Numerous tests were conducted for the best model fit. The variables in the model are listed in Table 1.

Table 1. Fraction Rating Fuel Economy as Most Important Attribute vs. Real Gas Price and Price Change

Year	Fraction rating fuel economy most important	4-year average of real gas price (1982-84, ¢/gal)	2-year rate of change in real gas price
1980	0.42	118.7	0.482
1981	0.20	129.6	0.225
1983	0.13	138.2	-0.173
1984	0.07	130.0	-0.131
1985	0.08	120.6	-0.096
1987	0.04	98.9	-0.243
1996	0.07	80.4	0.037
1998	0.04	77.5	-0.167

Let us define the three variables as follows:

f_y = fraction rating fuel economy most important in year y

$p_{y \text{ to } y-n}$ = real gasoline price (year y through y – n)

n +1 = the number of years averaged

$\Delta_{y \text{ to } y-m}$ = change in real gasoline prices from year y - m to year y

In the model for which we present estimates, n = 3 and m = 2. Generically, y = 0.

Since the dependent variable f is a fraction between 0 and 1.0, this is not a continuous distribution. A standard solution is to estimate the quantity ln[f/(1 - f)], which converts the fractional distribution to a continuous distribution between negative and positive infinity. We also convert the gasoline prices, which are always positive, into ln(p). Changes in prices are used as-is, since conversion to the logarithmic form is not possible for negative numbers. This gives us the following formula:

$$\ln[f/(1 - f)] = a + b\,\{\ln(p_{0 \text{ to } -3})] + c\,\Delta_{0 \text{ to } 2}$$

where "a" is an intercept term and "b" and "c" are coefficients. The coefficients of the model itself are not of great interest here. Rather, this is simply a test that the coefficients are positive and significant, to prove that the survey respondent's evaluation of the importance of fuel economy is related to both price level and rate of change of real gasoline price. The estimated equation, the t-values, and their p-values are given below:

$$\ln[f/(1-f)] = -9.91 + 1.65\,\{\ln(p_{0 \text{ to } -3})] + 3.21\,\Delta_{0 \text{ to } 2} \quad R^2 = 0.943$$

	(-4.49)	(3.51)	(7.51)	F = 41.1
	[0.004]	[0.013]	[0.000]	[0.001]

The t-values are reported in common parentheses () and p-values in block parentheses [ ]. The estimate indicates that both gasoline price and change in gasoline price level influence consumer attitudes about vehicle fuel economy. Over the late 1970s to the mid-1980s, the increase and following decrease in gasoline prices were larger than any others in U.S. history; in this same period, the diesel passenger car sharply gained market share and then lost it. The pattern of price changes over that interval might alone have caused the change in sales of diesel vehicles, but many also blame the diesels' hurried introduction and poor quality for the sales slump that came with declining gas prices.

Our results, plus experience with the passenger car diesel in 1978-87, imply that both level and rate of change of prices are important. If gasoline prices rise because of sharp movements in oil prices, the market share gained for FEVs may be lost when prices drop.

Although the fraction of respondents placing fuel economy at the top of the attribute list peaked at 0.42 in 1980, the peak fraction of sales for diesels was about 8% of the market, in 1981. Most of these sales were probably to consumers who chose to pay more for a vehicle to obtain higher fuel economy. These are likely candidates to buy HEVs when and where gasoline prices are high.

Vehicle Size

A pattern of shifting preference for fuel economy as a function of fuel price can also be seen in the mix of vehicles purchased. When gasoline prices rise, more fuel-efficient vehicles — made so, in part, by reducing their size — are purchased. Greene (1999, Fig. 10) has shown that the share of compact and subcompact cars is a positive function of gasoline price. The percentage of small cars jumped from the high 20s in 1977 to the high 40s in 1980, the peak year (also the peak year in Table 1).

The problem with targeting this group of consumers during a price rise is that they are not only seeking higher fuel economy, but also lower first cost in a vehicle. This group may account for a large fraction of the increase in percentage of respondents placing fuel economy at the top of the priority list, but they are not the best target market for introduction of a vehicle that costs more in order to obtain higher fuel economy.

In the hypothetical contemporary switch illustrated by Table 2, it is difficult to see the purchaser who switches from a mid-size to a compact car only to save fuel as "rational," in terms of net present value (NPV). Presumably, the consumer would otherwise prefer a mid-size car. In this example, about $4000 is saved by switching cars. Suppose that the consumer drove 13,000 miles per year for ten years (a bit above the annual U.S. rate, but it provides about the correct vehicle lifetime); obtained the fuel economy rating on the sticker of the vehicle; and, consistent with 1997 patterns, drove 63% in city driving and 37% in highway driving (FHWA, 1998). At a 20% discount rate, the value of the fuel savings at $1.25/gal is abut $700. It would take a gasoline price of $7.00/gal to make the fuel savings equal the reduction in vehicle cost.

Table 2. Fuel Economy Gains and Price Savings Achieved by Switching from 1999 Mid-size to Compact Cars

		Fuel Economy (mpg)		
Size	Vehicle and Engine	City	Highway	List Price
Mid-size	Dodge Stratus 2.5 L4	19	27	$19,060
Mid-size	Chevrolet Malibu 3.1 L4	20	29	$18,960
Mid-size	Ford Taurus 3.4 L4	16	25	$17,560
	Mean (harmonic)	18.2	26.9	$18,527
Compact	Dodge Neon 2.0 L3	23	32	$12,390
Compact	Chevrolet Prizm 1.8 L4	28	36	$14,964
Compact	Ford Contour 2.5 L4	20	29	$16,055
	Mean (harmonic)	23.2	32.1	$14,470
% Change		27%	19%	$4057 (22%)

For this analysis, it is assumed that gasoline prices and – implicitly – the economy are stable. In the 1980s, widespread switches to compact cars occurred after sharp rises in gasoline prices, at a time when the economy performed very poorly, and when future income levels were at risk of going down while future gasoline prices were projected by many to continue to rise. Under such circumstances, purchase of a more fuel-efficient *and* less expensive vehicle would be far more logical than under current conditions.

Although he did not relate it to general economic conditions and expectations for household income, Greene (1998) illustrated that consumers historically have made significant switches in vehicle size choice when gasoline prices changed significantly. In retrospect, this behavior seems reasonable if it is assumed that consumers, when purchasing a new vehicle, anticipated that gasoline price trends of the years immediately preceding the purchase would continue. Such an assumption matches with the indications of the statistical analysis above.

There is, however, another lesson to be learned. Since the mid-size car of 1999 is considerably more efficient than that of the 1970s, greater gasoline price increases than in 1978-1980 would be necessary to cause the fuel *cost* increases that would motivate the same kind of switch. This is one problem that the Prius-type HEV faces. It has to displace an already fuel-efficient vehicle in the marketplace.

Of course, any switching to more fuel-efficient vehicles is likely to be temporary if gasoline prices do not remain high. Over a decade ago, Santini and Vyas (1988) developed an equation projecting "symmetric" behavior in the reaction of new car fleet fuel economy to both short- and long-run changes in gasoline price. The equation included a long-run term with a seven-year lagged response to gasoline price. To the extent that this term is correct, gasoline prices not only have to rise to make hybrids and other FEVs competitive, but prices also have to remain high for a long time to have a significant effect.

Vehicle Performance

Consumers who bought diesels sacrificed performance in order to gain higher fuel economy. In fact, following the gasoline price run-up of 1978-1981, nearly all consumers gave up performance for fuel economy. While one may doubt the marketability of the 1999 Prius because of its "slow" 0-60 acceleration time of 14.3 seconds, it is worth remembering EPA estimates that the 0-60 time for cars in 1981 and 1982 was 14.4 seconds. For trucks in 1984, this value rose to 14.7 seconds (Heavenrich and Hellman, 1996). By today's standards, these vehicles are quite slow; recent averages are slightly less than 11 seconds. If gasoline prices do rise, though, the Prius's performance level could become acceptable. Note that the 14+ second values in the 1980s were *averages*. Four diesel cars tested by Consumers Union in 1980 averaged 0-60 times of 21.8 seconds (Consumer Reports, 1980).

Diesel engine technology has improved dramatically since the 1980s. The new diesels, which use "direct injection," can compete much more readily with gasoline engines. Nevertheless, evidence from Europe suggests that when gasoline and diesel fuel prices are high, consumers still are willing to accept vehicles with lesser performance to obtain higher fuel economy. In March 1999, the German magazine "mot" tested six diesels in pairs against the same-model gasoline vehicle, which they determined to be most comparable. According to these tests, the 0-100 km acceleration times of the diesels ranged from 16.8 to 9.7 seconds, averaging 13.3 seconds. The six gasoline vehicles that were compared to the diesels accelerated from 0-100 km/hr in from 17.9 to 8.9 seconds, averaging 12.2 seconds. The hundreds of vehicle tests summarized at the back of the magazine indicated that many vehicles sold in Europe have acceleration times in the high teens, and a few – generally diesels – still sell despite 0-100 km/hr acceleration times in excess of 20 seconds (mot, 1999).

These indications imply that U.S. consumers will accept lesser performance in the event of a sharp gasoline price increase. A gasoline price shock would be most likely to create a market opportunity for the HEV, as it did in the early 1980s for the diesel. In one of the cases we consider, we examine a trade of a current performance gasoline vehicle for the lower-performance Prius-type HEV.

Predicting Prices

Consumers react to price rises by adopting a preference for fuel economy and shifting to smaller, more fuel-efficient vehicles. Once prices rise, consumers evaluate future prices as if they will at least remain the same, anticipating a continuation of the recent trend. The EIA does not necessarily predict prices in the same way as the consumer, but we examine EIA predictions to provide some perspective on prior assertions. In Figure 1, we plot the EIA's crude oil price predictions for the future year (six years in advance of the year of the prediction) for various years, 1982 to 1991. We add to the plot the prices in the years 1978-1982, a reminder of the oil price run-up of that period. We also plot the actual values (consistently lower) and a measure of the error in the forecast. Two key points are illustrated. First, the forecast prices largely move in lockstep with current prices. If current prices rise (fall), the forecast for six years in the future rises (falls) similarly. Second, the errors are larger in a positive direction after the price shocks of 1978-1981 and 1988-1990, implying that positive shocks give an upward "boost" to the forecast price. We speculated earlier that such tendencies also exist for consumers: when gasoline prices rise, consumers project that they will stay high, and they tend to adjust forecasts slightly upward on the assumption that these positive changes are likely to continue, to some degree, into the future.

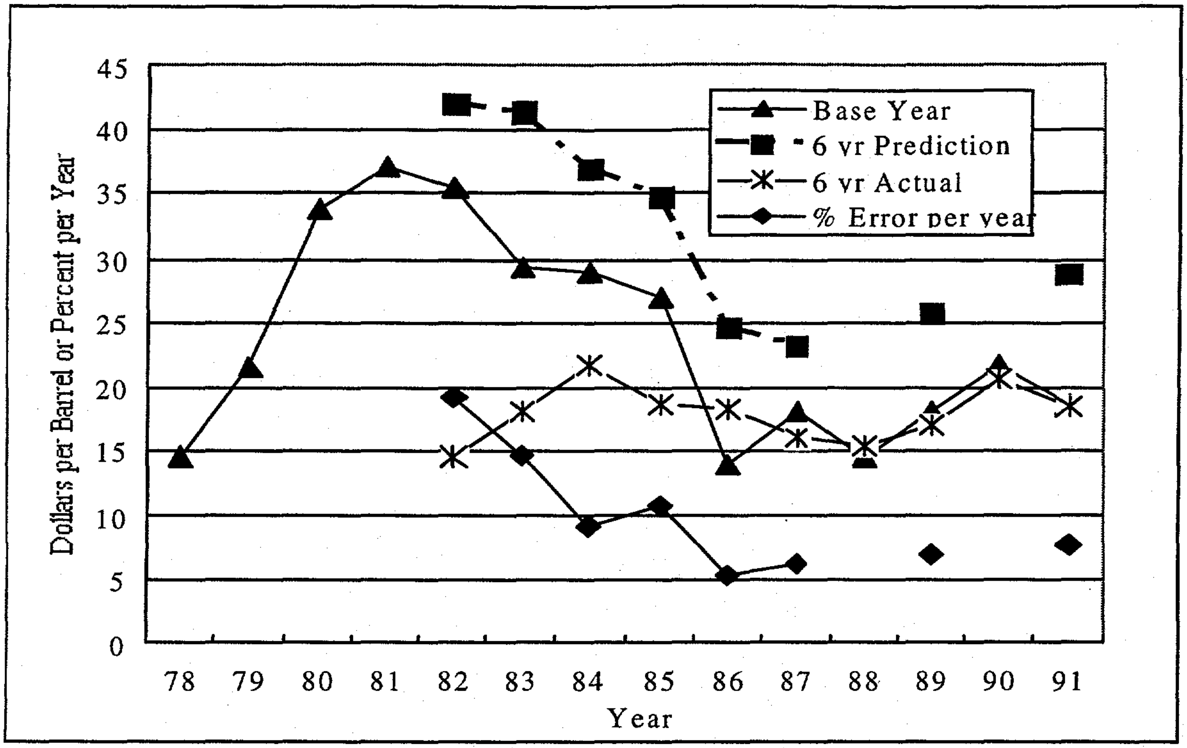

Fig. 1. A History of EIA Predictions of Oil Prices Six Years Ahead – Comparisons with Actual Values and Percent Errors in the Forecasted Annual Rate of Price Change

The Discount Rate and Present Value

FEVs are potentially attractive to new vehicle buyers because they can reduce the amount of money spent on motor fuel in the future. The discounted value of these fuel savings is called the present value of future savings. The present value must equal or exceed the incremental purchase price of the HEV to have the buyer make an economically rational decision to purchase it.

Greene argues that these methods result in discount rates that are too low, because they ignore the fact that the vehicle will eventually depreciate to a zero value (unlike a normal market investment). When this fact is taken into account, along with the fact that vehicle miles traveled decline with vehicle age, Greene finds the "correct" discount rate is about twice that normally used (Greene, 1999).

Importance of Estimated Future Fuel Prices to Interpretation of Consumer Behavior

Greene's analysis of the consumer's discount rate is a recent one. However, from 1996 to 1998, there was a significant drop in real gasoline prices. Furthermore, the real gasoline price has dropped considerably since 1983. If consumers assume that the trend in price will continue, and if they purchase a vehicle under that assumption, then an *analyst's* evaluation of their behavior (which incorrectly assumes that consumers expect prices to be flat) will conclude that consumers are using a higher discount rate than they actually are. Alternatively, if gasoline prices are rising, and consumers assume that they will continue to rise, while *analysts* of consumer behavior treat the consumer as if flat gasoline prices are assumed, then the analyst will conclude that consumers are using an unusually low discount rate.

Surveys of the Value of Fuel Economy

Given the uncertainty over the credibility of survey responses, the following survey results need to be considered cautiously. (A market analyst with one of the domestic auto companies once said that he reduces by 75% any market share for a new technology obtained from a survey.)

In recent telephone surveys, a representative sample of the adult population were asked several questions about fuel economy, as requested by DOE. In early 1999, 847 respondents were asked to name the single most important reason they bought their most recently purchased new vehicle. This was an unaided question; with no answers suggested. Fuel economy was the most important reason for 5% of the respondents. For small-car owners, 12% listed fuel economy as the most important reason (Opinion Research, 1999). Thus, a small but important segment of the vehicle-buying public values fuel economy in spite of the low importance most commentators place on it today.

In 1998, 1019 respondents were asked how much extra they would pay to purchase a vehicle with 2X and 3X fuel economy (a base vehicle price of $20,000 was specified). The results of this survey are shown in Table 3 (Opinion Research, 1998). The average amount respondents say they are willing to spend to double fuel economy is $2563 (this includes the 13% who are not willing to pay anything). The distribution of respondents by payment class shows that 30% are willing to pay between $2000 and $5000 for a 2X vehicle, which is probably going to be the incremental cost of such a vehicle when it is made available in the next 10 years. But what do the responses mean in terms of mileage driven, type of base vehicle assumed, and interest rate? Various combinations and permutations are possible. We illustrate a few.

Table 3. Percent Willing to Pay Given Amounts for a Doubling of Fuel Economy

Population	$0	$500 or Less	$501-$1000	$1001-$2000	$2001-$5000	More than $5000	Mean
Total	13	6	13	21	30	5	2563
25-34 yr	9	6	15	18	38	7	2876
45-54 yr	18	5	7	20	38	4	2648
West	11	4	11	22	35	5	2819
>$50K	10	5	11	25	37	5	2767

If we use the simplified model of 13,000 miles annual driving for 10 years, a 20% discount rate, and $1.25/gal gasoline price, then a compact car owner able to double fuel economy should be willing to pay about $1300 for it. A mid-size owner should be willing to pay $1650 for a mid-size that doubles fuel economy, and an owner of a base sport utility vehicle, such as a Chevrolet Blazer or Ford Explorer, should be willing to pay about $1950. If the consumers surveyed choose a mix of interest rates in their evaluations, those who choose an 8% discount rate would be willing to pay an extra $2000 for the 2X compact car, $2600 for the 2X mid-size, and $3100 for the 2X SUV. One way to get into the $5000 range is to assume a pickup truck driven 26,000 miles per year for seven years at an interest rate of 8%. To get into the $500 range, one needs to assume that the respondent had a high-fuel-economy subcompact car in mind as the base vehicle and only drives about 6500 mi/yr. To obtain a value of $0, one has to abandon notions of economic rationality.

Disaggregation of Preference Patterns

Having examined the issue of variation of preferences for fuel economy as a function of fuel price level and rate of change, we turn to variation by type of car chosen, by income, and by education. A National Opinion Research survey conducted on Feb. 25,1999, which included DOE-specified questions, indicates considerable difference in desire for fuel economy by type of vehicle purchased.

In Table 4, we show the percent responding affirmatively to the request to identify an attribute as the single most important reason for purchase. Included are the percentages for vehicle price and fuel economy. Another national survey, conducted a few years before, estimated coefficients for the importance of fuel cost and purchase price (Tompkins et al., 1998). Estimates constructed since that publication of survey results have been divided into the same vehicle size categories as for the Feb. 25 survey. The coefficients for one of those models are presented in the last two rows of Table 4. The two surveys are consistent in estimating that consumers who choose to purchase small cars place the importance of vehicle price and fuel cost at a higher level than consumers who choose or consider any of the other categories of vehicles. It appears that the drop-off in importance of fuel economy for vehicles other than small cars in Feb. 1999 was more dramatic than that seen in the national survey conducted by Tompkins et al. from Aug. 1995 to Jan. 1996, when real gasoline prices were more than 25% higher. As of Feb. 1999, crude oil and gasoline prices had been dropping sharply.

Table 4. Percent Responding Affirmatively on Primary Importance or Model Coefficient

Variable	Total	Small Car	Large Car	Minivan	Sport Utility	Pickup/ Large Van
Fuel economy/ gas mileage (%)	5	12	1	2	1	4
Price/value (%)	13	18	14	3	4	10
Fuel cost (¢/mi.)*	N/A	-0.11	-0.086	0.042	-0.11	-0.054
Purchase price ($\$10^3$)*	N/A	-0.068	-0.041	-0.11	-0.035	-0.073

* Coefficient from "model 33" of national survey by Tompkins et al. (1998).

One notable inconsistency between these two surveys is the importance of fuel economy for sport utility vehicles relative to the value for small cars. In the 1995-1996 survey, the fuel cost coefficient for SUVs was a close second to that for small cars, while the Feb. 1999 survey indicated that fuel economy for SUVs was unimportant.

The Feb. 1999 survey also indicated that the importance of fuel economy was about twice as great for households with incomes less than $35,000 (7-8%) in comparison to those with incomes above this level (3-4%). This is unfortunate because it is those households with incomes above $35,000 that purchase the vast majority of new vehicles and therefore determine the fuel economy mix of used vehicles that those with lower incomes purchase.

Finally, the Feb. 1999 survey also indicated that those who had not gone beyond high school placed a higher value on fuel economy (7-9%) than those who had attended or completed college (3-5%). This result is very consistent with the income result, since those with some college or college degrees undoubtedly have higher income.

These results imply that the introduction of the HEV technology in a small car is a good idea to the extent that those who purchase these vehicles place the highest value on fuel economy. On the other hand, since they also place a high value on reasonable purchase price, small-car buyers are likely to scrutinize the vehicle purchase price increment relative to fuel savings more carefully than would consumers who select other classes of vehicles. Were the preference for fuel economy by SUV buyers actually strong, but purchase price weak, this market could be more favorable. The evidence in Table 4 is inconclusive in this regard.

III. WILL SMALL CAR BUYERS PURCHASE PRIUS-TYPE HEVS?

If small-car buyers are value-oriented and are the most likely to use net present value thinking in their evaluation of an HEV, what will they conclude? Of those who evaluate vehicles in this way, how many will be swayed to purchase an HEV?

Fuel Consumption Properties of HEVs vs. Conventional Vehicles

The properties of Prius-type HEVs vs. conventional vehicles are detailed elsewhere (An, Stodolsky, and Santini; Santini et al.; Santini and Vyas). Santini and Vyas observed that the fuel savings per hour as a function of average driving speed are remarkably constant across speeds for a Prius-type HEV, whereas fuel economy drops steadily in a conventional gasoline vehicle as speed decreases. At higher speeds, the presence of the more efficient

Atkinson-cycle engine in a Prius keeps the estimated gains significant: otherwise, with an engine technologically identical to a competing conventional vehicle, fuel economy benefits disappear at higher average speeds.

Using statistical methods and judgment based on results of prior studies – particularly An, Stodolsky, and Santini – we have developed estimates of in-use fuel consumption as a function of driving speed for three vehicles. The first is a 1997 Toyota Corolla with automatic transmission, estimated to be capable of accelerating from 0-60 mph in 11 seconds. The second is the Prius, tested to accelerate from 0-60 in a bit over 14 seconds. The third is a so-called MHV, simulated to be capable of accelerating from 0-60 in 11 seconds. The MHV does not provide as high a fuel economy gain as the Prius does, but it is faster and costs less. (See An, Stodolsky, and Santini for technical details.)

The estimated fuel savings per hour from substituting the MHV and the Prius for the Corolla are shown in Table 5. Compared to Vyas and Santini, the Prius savings estimated here are slightly higher, due to an adjustment to account for in-use fuel consumption rather than dynamometer-test fuel consumption.

Table 5. Estimates of Fuel Consumption and Savings: Small HEVs vs. Conventional Vehicle

Speed (mph)	Corolla (gal/h)	MHV (gal/h)	Prius (gal/h)	MHV Savings (gal/h)	Prius Savings (gal/h)
5	0.41	0.20	0.15	0.21	0.25
15	0.66	0.38	0.31	0.29	0.36
25	0.92	0.60	0.52	0.32	0.40
35	1.18	0.86	0.81	0.31	0.37
45	1.43	1.18	1.14	0.26	0.29
55	1.69	1.51	1.46	0.18	0.23
65	1.95	1.84	1.66	0.11	0.29

Estimating Dollar Benefits

Our assumptions about battery life and replacement are important. We examine two possible battery life assumptions: the battery is anticipated to last (a) 100,000 kilometers (62,150 miles), or (b) six years. In Vyas et al. (1997), survey respondents predicted that future nickel metal hydride batteries would have a shelf life of six years.

It remains to be determined how long battery packs will last in use under the considerably different patterns of driving in Asia, Europe, and North America. According to Kenworthy and Laube (1999), Asian work trips average around 15 mph, with a time range of 20-44 minutes (means over 32); in European nations, the average is about 21 mph and the time range is 20-35 minutes (mean of 28); and for the U.S., Canada, and Australia, the average is 27-34 mph, with a time range of 22-31 minutes (mean of about 26).

We assume that a specified vehicle is consistently driven for the same number of hours per year, at the same average speed, until scrapped. We also assume: that a vehicle is driven until the last battery pack fails; no vehicle will have its life extended through more than three battery packs; and maximum vehicle life is 12 years. In the estimates we constructed (most not presented), the distance driven was based on speed and 1.25 to 2.5 hours of driving per day. The average U.S. driver spends about 1.2 hours per day in the vehicle (based on an unweighted average from the National Personal Transportation Survey [NPTS]). When we use the 2.5-hour figure, we are targeting consumers who can use the HEV intensively, those who presumably can retrieve the added purchase cost and battery pack cost through fuel savings most rapidly. We use the NPTS to estimate the percentage of consumers who travel at a specified speed and number of hours per day. This is only an approximation for illustration, based on the one-day trip file. We discuss estimates based on fuel cost of $1.50 and $2.25 per gallon, in 1999 dollars.

In 1997, U.S. gasoline prices averaged $1.29/gal; in 1998, $1.12/gal. Prices are generally higher in California and New York. As pointed out earlier, the U.S. has experienced real gasoline prices in excess of $2.40/gal in 1999 dollars; many analysts doubt that this will ever happen again. Prices above $3.00/gal exist in Japan and Europe.

We conducted evaluations at real interest rates of 8% and 20%. The 20% interest rate nearly always meant that the NPV of benefits was negative, so we present only the 8% results. While a real interest rate of 8% is a high rate in historical terms, it is not high relative to estimates of average consumer behavior in evaluating fuel economy. The purchasers of small cars (such as the Prius) place a relatively high value on fuel economy, so they are probably more likely than most to use a low rate of interest when evaluating the fuel economy vs. purchase price trade-off.

For estimates presented here, the first year of vehicle life was assumed to be about a decade hence (2009). Our estimates extend to 2016 and include further declines in HEV price increment. We also examined a case with a lower price increment. We assume low volume sales in the U.S. through most of the decade, with offshore HEV manufacturers "working out the bugs" and testing the U.S. market while producing and selling hundreds of thousands of vehicles in other industrialized nations with high gasoline costs (i.e., the customer acceptance and confidence problems involved in introducing a dramatically new technology are first resolved in other nations.) We assume that only when the technology is proven elsewhere will it be marketed in high volumes in the United States.

Batteries were assumed to decline in 1999 dollar cost through 2016, remaining constant in cost thereafter. The incremental retail price of the "slow" Prius in 2009 was estimated to be $3750 and that of the "fast" MHV to be $3200. (Toyota indicates that the U.S. Prius will have better acceleration than the one presently produced.) The battery pack costs for the Prius drop from $1572 in 2009 to $1236 in 2016; replacement battery pack costs for the MHV drop from $1290 to $1090 over the same interval. Table 6, one of numerous tables constructed, shows how the estimates were developed. Interpretation and presentation of the experiments is beyond the scope of this paper.

Table 6. HEV Savings at 2.5 h/d, $2.25/gal, i = 8% ($3200 MHV, $3750 Prius price increments)

Battery Life Basis	Speed (mph)	Life (10^3 mi)	Years to Scrap	Years to Battery Replace-ment	MHV Increase ($)	MHV Savings ($)	MHV NPV ($)	Prius Increase ($)	Prius Savings ($)	Prius NPV ($)
6 yr	5	55	12	6	3582	3600	18	4192	4,470	278
62K mi	15	123	9	4.5	4,033	4,274	241	4,728	5,328	600
6 yr	15	164	12	6	3582	5033	1451	4192	6273	2081
62K mi	25	182	8	2.7,5.3	4,981	4,487	(494)	5,863	5,535	(328)
6 yr	25	274	12	6	3582	5674	2092	4192	6968	2766
62K mi	35	182	5.7	1.9,3.8	5,164	3,614	(1550)	6,093	4,251	(1842)
6 yr	35	383	12	6	3582	5481	1899	4192	6448	2256
6 yr	45	493	12	6	3582	4544	962	4192	5099	907
6 yr	55	602	12	6	3582	3166	(416)	4192	4097	(95)

The results imply that if the batteries last only 100,000 km (62000 mi), the market is pushed toward vehicles driven very slowly on average, and there are few of these in the U.S. In the NPTS one-day sample, about 1.7% of national trips took more than 2 hours and were driven at speeds of 20 mph or less. In California, this value is 1.6%, and in the major metro areas of the Northeast, it is 2.5%. If battery life proves to be a function of time after manufacture (shelf life), rather than miles, the size of the U.S. market should expand significantly on a percentage basis, though it may still be small. When we assumed 1.25 h/d of driving, $1.50/gal for gasoline, an interest rate of 8%, a MHV incremental price of $2050, and a Prius incremental price of $2400, in every case the results implied losses to the owner. When we increased the gasoline price to $2.25/gal, savings of hundreds of dollars were estimated for both the MHV and Prius at speeds of 15 and 25 mph — whether the battery was assumed to last either 62,000 miles or six years. At 35 mph, if the battery lasted six years, hundreds of dollars of benefit were estimated, but if the pack lasted only 62,000 miles, losses of several hundred dollars were estimated. Kenworthy and Laube estimated the average speed for commuting to work in the U.S. as 35 mph. In all other cases, losses were estimated.

The Japan10/15 mode driving cycle, used to rate vehicles in Japan, averages 15 mph; the European ECE-15 test cycle averages 21 mph; and the Corporate Average Fuel Economy rating of U.S. vehicles is based on a weighted average of two driving cycles averaging 33 mph. Note the consistency of these official test cycle speeds with the field test results cited by Kenworthy and Laube. As Santini and Vyas (1999) have noted elsewhere, when batteries are assumed to last 62,000 miles, the long-run net benefits of a Prius-type HEV vs. a gasoline CV appear to be positive for the *average* driver in Japan, about even in Germany, and negative in the U.S. Gasoline prices in Canada were between $1.50 and $2.00/gal, and in Australia between $2.00 and $2.25/gal, in 1997-1998. Commuting speeds are 27 mph in Canada and 29 mph in Australia. If the low price increments for the HEVs prove to be correct, the

HEVs characterized should be attractive to the average consumer in Australia, if batteries last nearly six years and gasoline prices remain close to present values.

IV. CONCLUSIONS

Our analysis, with the HEV vs. CV price increment estimates for the moderate-performance, compact/small vehicles examined here, and current fuel savings estimates valued at U.S. gasoline prices, implies that the U.S. market for such HEVs would be quite limited. However, these projections could prove to be in need of modification in the future. One key unknown is battery life in U.S. driving conditions. The estimates made depend heavily on the electric drive and battery costs used, and on many other assumptions related to configuration and performance. Even though this is a new, evolving technology, the estimates made do have implications. In the event of (1) gasoline prices rising to $2.25/gal (1999$), (2) battery life of six years or more, (3) higher than average hours of driving per day, and (4) low incremental price premiums, this analysis implies that a significant U.S. household market niche could emerge for the HEV types evaluated here. A gasoline price rise like that over the 1973-1981 period might cause many HEVs to enter the market, but a subsequent decline would likely mean a reversal of fortune for them. At present gasoline prices, the success of such HEVs in the U.S. may depend on customers having altruistic motives, or on features of the vehicles other than those examined here.

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