Commercial Viability of Hybrid Vehicles: Best Household Use and Cross National Considerations

by

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Abstract

Japanese automakers have introduced hybrid passenger cars in Japan and will soon do so in the United States. In this paper, we report how we used early computer simulation model results to compare the commercial viability of a hypothetical near-term (next decade) hybrid mid-size passenger car configuration under varying fuel price and driving patterns. The fuel prices and driving patterns evaluated are designed to span likely values for major OECD nations. Two types of models are used. One allows the "design" of a hybrid to a specified set of performance requirements and the prediction of fuel economy under a number of possible driving patterns (called driving cycles). Another provides an estimate of the incremental cost of the hybrid in comparison to a comparably performing conventional vehicle. In this paper, the models are applied to predict the NPV cost of conventional gasoline-fueled vehicles vs. parallel hybrid vehicles. The parallel hybrids are assumed to (1) be produced at high volume, (2) use nickel metal hydride battery packs, and (3) have high-strength steel bodies. The conventional vehicle also is assumed to have a high- strength steel body. The simulated vehicles are held constant in many respects, including 0-60 time, engine type, aerodynamic drag coefficient, tire rolling resistance, and frontal area. The hybrids analyzed use the minimum size battery pack and motor to meet specified 0-60 times. A key characteristic affecting commercial viability is noted and quantified: that hybrids achieve the most pronounced fuel economy increase (best use) in slow, average-speed, stop-and-go driving; but when households consistently drive these vehicles under these conditions, they tend to travel fewer miles than average vehicles. We find that hours driven is a more valuable measure than miles. Estimates are developed concerning hours of use of household vehicles versus driving cycle, and the pattern of minimum NPV incremental cost (or benefit) of selecting the hybrid over the conventional vehicle at various fuel prices is illustrated. These results are based on data from various OECD nations on fuel price, annual miles of travel per vehicle, and driving cycles assumed to be applicable in those nations. Scatter in results plotted as a function of average speed, related to details of driving cycles and the vehicles selected for analysis, is discussed.

Background

In this paper, we evaluate the economic viability of a hybrid passenger car like Toyota's Prius, which is now produced and sold in Japan. The Prius is scheduled for introduction in the United States. The body of the vehicle is conventional; the materials and manufacturing techniques that are used in its production are the same as those used in the production of Toyota's Corolla. The drivetrain, however, is very unconventional: it uses an "Atkinson cycle" engine and a unique planetary gear transmission, along with a generator, a motor (electric), and a battery pack, as well as a systems control strategy developed by Toyota. The nature of the vehicle, with considerable technical detail, was provided in a press package prepared by Toyota in 1997. That press package (and recent consumer information sheets) indicates that the vehicle can double fuel economy (the actual Japanese test cycle for which this claim is made is duly noted by Toyota) and reduce emissions by 90% (Toyota, 1997). Although we do not discuss emissions in this paper, we do note that U.S. emissions benefits do not match the 90% value stated in the press release, and they depend on the vehicle-to-vehicle comparison made under U.S. test procedures. See Santini et al. (1999) for a discussion of Toyota's emissions reduction claims and Hellman, Peralta and Piotrowski for emission test results relative to U.S. passenger cars.

Technical experts generally agree that a hybrid vehicle will provide greater fuel economy benefits relative to a conventional gasoline vehicle when driven in stop-and-go urban driving conditions. MacCready (1993) noted that "One conclusion to draw is that the best vehicle for the urban driving cycle (which in many locations is becoming the gridlock style) may be a rather different vehicle from one used primarily for high speed driving with few stops. ... The customer will be offered choices that emphasize one type of driving more than the other, but the vehicle will handle the other type adequately. ... The net consequence is that, from a fuel economy standpoint, the hybrid looks attractive for low speeds and stop and go driving, and moderately attractive even at higher speeds." More recently, others have asserted that vehicle simulation modeling does not estimate that a doubling of fuel economy can be obtained under U.S. driving conditions (Wang, 1997). Even more recently, the U.S. Environmental Protection Agency [EPA] has published actual test data on fuel economy under U.S. driving conditions (Bedard, 1999; Hellman, Peralta and Piotrowski, 1998). According to the latter EPA estimates, the tested Prius will exceed the fuel economy performance of a comparable gasoline vehicle by 45% on the U.S. Corporate Average Fuel Economy (CAFE) test. Compared with the 1998 Toyota Corolla with a four-speed automatic transmission, the Prius obtains about a 60% mpg increase in city driving and about a 15% mpg increase in highway driving (Hellman, Peralta, and Piotrowsky, 1998; U.S. Department of Energy, 1997). More recently, in a technical forum, Toyota has presented its own results of Prius vs. conventional vehicle tests for five different driving cycles, including those used in the United States (Hermance, 1999). Fuel cell hybrids appear to be likely to have the same property; that is, a larger jump in city fuel economy than highway fuel economy in comparison with conventional gasoline vehicles. The ratio of the city-to-highway CAFE test-measured fuel economy for the Toyota Corolla is 67% (U.S. Department of Energy, 1997); for simulated fuel cell vehicles, the ratio varies from 80% to 96% (Doss, Ahluwalia, and Kumar, 1998; Oei et al., 1997).

Lovins (1995) characterized the "Ultima," hypothetical ultralight hybrid to be introduced in the late 1990s. It was projected to be more than twice as efficient as the average 1990 U.S. car, perhaps even as much as three times as efficient — in city driving — but this car's efficiency (relative to its own city driving) fell in highway driving "because there is far more irrecoverable loss to air drag ... and less recoverable loss to braking." The Partnership for a New Generation of Vehicles (PNGV) "Goal 3" is to produce a vehicle that can triple fuel economy on the CAFE cycle, which combines city (55%) and highway driving (45%) fuel consumption. Thus, the PNGV goal exceeds the fuel efficiency gain implied (in Lovins' Fig. 5-1) to be possible, although it allows a few more years to reach that goal (2004).

In table 7-5, Duleep (1997) estimated that a 64–65 mpg (CAFE combined city/highway) mid-size passenger car, using gasoline in a conventional vehicle technology package, would cost more than one obtaining the same mpg using hybrid vehicle technology. However, Duleep estimated that an advanced diesel could obtain about 59 mpg — at about half the incremental cost of the 64–65 mpg gasoline hybrid or gasoline conventional vehicle. At present, there is little consumer demand in the United States for vehicles that obtain better fuel economy

(Stoffer, 1999), although Volkswagen has reentered the diesel market in the United States by marketing models in the same EPA size class as the Toyota Prius. With a manual transmission, the VW Golf and 1999 Jetta obtain a CAFE rating of 53 mpg. However, the appropriate comparison is between an automatic-equipped Golf or Jetta and the Prius since the Prius transmission is even smoother than an automatic transmission, with no gear shifts. The automatic transmission models of these two VW diesels each obtain a CAFE rating of 45 mpg. We note that VW originally offered the manual transmission-equipped diesel in the mid-size Passat (USDOE, 1997, 1998), but VW has since apparently dropped the diesel option in this size class (USDOE, 1998), retaining it in the compact Golf and Jetta models. Perhaps, fuel-economy-conscious U.S. buyers seek vehicles with both low initial cost and low operating cost. Although the Prius is not yet rated (and is likely to be improved somewhat in the version that is offered to U.S. customers), its CAFE rating, if based on EPA research tests, would be about 50 mpg, with slightly higher urban fuel economy than the VW diesels and slightly lower highway fuel economy.

The long-term viability of the diesel hinges not only on its fuel economy but on its emissions performance. The Prius hybrid is more promising in this respect, but the topic is beyond the scope of this paper.

The Potential Fuel Economy Gains of a Hybrid-for-Conventional-Gasoline Vehicle Switch

The Prius, on the basis of interior volume, falls into the highest-volume-selling size class in the world, what is called the compact by the U.S. EPA (Hellman, Peralta, and Piotrowsky, 1998). The compact hybrid vehicle is compared with conventional gasoline vehicles with comparable performance. In fact, the performance criterion used allows a "break" to the hybrid in the area of hill climbing. The hybrid is required to accelerate in normal use as well as the gasoline vehicle against which it is compared. In Fig. 1, we illustrate the gain in mpg possible by selecting a hybrid vehicle rather than a comparably performing gasoline vehicle as a function of average speed for four different driving cycles. A driving cycle is a speed time trace intended to be a somewhat reasonable depiction of reality. In fact, most driving cycles used to certify the emissions and fuel economy of light motor vehicles today are not adequate to represent real- world driving and are being modified as a result. (See Santini [1999] for some discussion of this situation.) Aside from the NYCC (New York City Cycle) cases shown in Fig. 1, the driving cycles shown are the old cycles, the acceleration and deceleration rates of which are not as demanding of a vehicle as is real-world driving. The Japanese 10/15 cycle is the certification cycle used in Japan, and the Fig. 1 results for this cycle, as noted earlier, were used in the initial English language press package on the Prius vehicle. The additional results are those recently presented by Hermance (1999), who showed the comparison made by Toyota to a Carina 1.5-L vehicle equipped with an automatic transmission. This model is not available in the United States. Toyota has tested the Prius and the Carina in the four driving cycles shown in Fig. 1, and in the ECE (Economic Community of Europe) driving cycle, which is not included in Fig. 1. The estimated mpg gain result for the ECE cycle was 0.5. The ECE cycle is the official certification cycle for nearly all of Europe. Accordingly, this paper uses the ECE gain result to estimate benefits in European driving. The FTP, or Federal Test Procedure, and the "LA-4" driving cycle are the same in most respects, with weighting factors among "bags" accounting for differences. For purposes of this paper, we regard them as identical. The FTP provides the raw data for the "city" fuel economy rating seen in the Gas Mileage Guide (GMG; USDOE, 1997). The U.S. Highway Fuel Economy Test (HFET), referred to as "U.S. Highway" in Fig. 1, is the source of data for the "hwy" rating seen in the GMG. The CAFE rating of a vehicle can be "backed out" from the GMG by manipulation of the following formula:

$$^1/_{\text{CAFE}} = 0.55*(^1/_{\text{city mpg}}) + 0.45*(^1/_{\text{hwy mpg}})$$

As can be seen in this formula, it is assumed that U.S. drivers drive 55% of miles in city driving and 45% in highway driving.

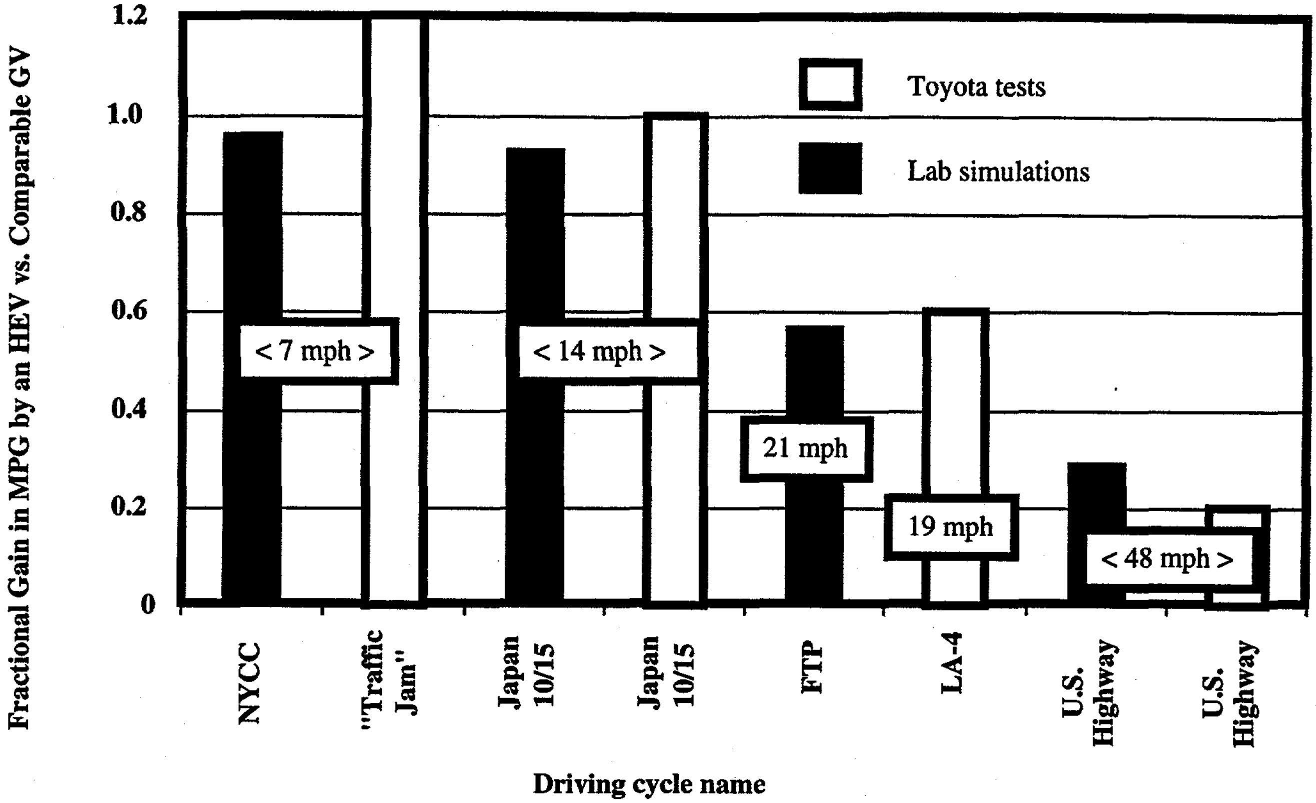

Fig. 1 Performance-Comparable Fuel Economy Gains Possible with a Hybrid Vehicle: Simulated and Tested

A team of analysts working for Argonne National Laboratory (ANL) and the National Renewable Energy Laboratory (NREL) refined and calibrated the Advanced Vehicle Simulator (ADVISOR) model developed at NREL for the purpose of comparing performance-comparable conventional gasoline and Prius-like hybrids. A paper documenting the results of that effort were submitted in March 1999 and published and presented in June of 1999 (Santini, 1999). The ADVISOR model was not able to simulate the type of transmission used by the Prius, so the authors simulated a hybrid with a conventional manual transmission. They speculated that the Pruis transmission should accomplish the same things that a continuously variable transmission (CVT) accomplishes in a conventional vehicle, speculating that the simulation most likely underestimated fuel economy more in the slower urban driving cycles than in the highway cycles because of the absence of the CVT-type transmission submodel in the ADVISOR model. That study, using EPA Prius test results for real behavior, was consistent in its presumed hybrid gain estimates with what is seen in Fig. 1 (i.e., the model slightly underestimates the urban fuel economy benefits possible with the Prius). Although Hellman, Peralta, and Piotrowsky (1998) had developed test results for an actual Prius, they had not conducted tests of a comparable gasoline vehicle for comparison, as Toyota has since done (Hermance, 1999, and Fig. 1). It is also possible that the apparent ANL/NREL Advisor overestimate in Fig. 1 for the highway driving cycle is due also to differences between a CVT and a conventional automatic transmission. The contemporary automatic transmission locks up mechanically in higher gears when cruising, while a CVT may have more slip. In any case, the Toyota results shown in Fig. 1 were not available to the team simulating the potential performance-comparable gains through hybridization, so the good comparability of the results is gratifying.

For this paper, the key point is that the key determinants of variation in fuel economy of hybrids and conventional vehicles are understood and reasonably predictable. Although there are good reasons to believe that the hybrid vehicle design can be adapted to U.S. conditions (and improved somewhat, as Toyota asserts), there are not likely to be any major surprises. In this paper, we use the recent Toyota comparative results in our calculations.

Household Behavior Interactions with Hybrid Vehicle Characteristics for Major Industrialized Nations

A hypothesis of this analysis was that one should think of driving behavior first in terms of hours that the consumer is willing to spend behind the wheel of a vehicle. This is not the perspective addressed in the preceding section. In the typical perspective, the fuel economy rating of a vehicle is fuel consumed per mile under the certification driving cycle in question although the United States uses miles per gallon. Although consumers are asked to, and normally do, think about fuel consumption in terms of per mile that they expect to drive, we suspect that their travel behavior is more closely tied to the amount of time they are willing to spend in the car. We have not taken the time to explore the literature to examine the soundness of this perspective, but it seems to fall out of the other numbers that we have collected, as shown below. In the event that the consumer resides in an area where travel is quite congested and slow, we assert that, on average, that consumer will select a place of residence that allows the household members who drive to spend no more than an hour and a half per day in the car, and preferably less. The Nationwide Personal Transportation Survey (NPTS, 1997) supports this generalization for the United States, but we include no references directly reporting travel times for Europe or Japan.

Note in Fig. 1 that the certification driving cycle in Japan averages 14 mph. Hermance (1999) reports that the ECE cycle, used in most of Europe, is a 21-mph cycle. The CAFE cycle, intended to represent U.S. behavior, averages 33 mph. So, if households across nations are similar with respect to the amount of time that they are willing to spend in the car, the annual miles traveled in Japan, Europe, and the United States should be inversely related to the average speed chosen for the representative driving cycle. Although this relationship is not followed exactly, the differences are fairly consistent with the above assertions. On the basis of the data in Tables 3.1 and 1.8 in Davis (1997), the annual miles of travel in Japan are 6648; in Germany, 8047; in France, 8878; in the Netherlands, 9410; in the United Kingdom, 9476; and in the United States, 11,400. Using the Federal Highway Administration's *Highway Statistics Summary to 1995* and *Highway Statistics '97,* we observe that the share of urban driving has gone from about 55% when the CAFE regulations were written to 63% today. Accordingly, we make the assumption that driving today is a 63% mix of city driving and 37% highway driving. Using this assumption for the United States and the mph values for city and highway driving, we estimate that the average U.S. driver is in a vehicle 1.24 h/day. For Japan, we estimate 1.29 h/day in the vehicle, while in the four European nations cited above, the estimated hours/day vary from 1.05 in Germany to 1.24 in the United Kingdom. These values are obviously quite similar and consistent with the hypothesis stated above.

Regarding the average new passenger-car fuel economy realized in the various nations that we examined, values were obtained from Table 1.5 of Davis (1997). These indicated 24.2 mpg for the United States, 31.9 for the Economic Community of Europe (ECE), 35.9 for France (a high percent of diesels), 30.8 for Germany, 37.0 for the Netherlands, 30.6 for the United Kingdom, and 26.1 for Japan. In the characterization of the performance-comparable (to the Prius) compact conventional car (Case 4 of Santini et al., 1999), the Japan 10/15 mode fuel economy was 26.6 mpg, which is essentially identical to Japan's new vehicle fuel economy as reported in Davis. For the FTP, the average speed of which is about the same as the ECE test, 30.2 mpg was obtained, which is about the same as that obtained for Germany and the United Kingdom. For the United States, however, the CAFE mpg obtained was 35.9, which is well above the average for the United States found in Davis. This occurs for two reasons: first, the performance of the simulated vehicle and the tested Prius is poor by U.S. standards, but likely representative elsewhere; second is the likelihood that the compact-size car represents the average car in Europe and Japan reasonably well, but it is a considerably smaller, more efficient car than the U.S. average. If we use the 1996 U.S. compact car fuel economy from Heavenrich and Hellman (1996), we obtain an estimate of on-road fuel economy of 25.6 mpg for compact cars in the United States, which is slightly higher than new car average mpg cited by Davis. Note that the compact car in 1996 held 36% of the passenger car market, more than any of the other five EPA size classifications, and 10% more than the next largest selling size class: mid-size.

The CAFE rating for 1996 compact cars in the United States was 30.7 mpg, which is well below the 35.9 mpg value for the low-performance compact characterized by Santini et al. The 0–60 acceleration time of the Prius and the competing conventional vehicle characterized by Santini et al. was 14.3 s. This is quite slow by U.S. standards. However, based on examination of (hundreds) 0–100-km/h times in the German magazine "Mot" (March 6, 1999), this time is certainly within a normal range and, perhaps, depending on sales weights, even average. Reportedly, the Prius is selling well in Japan, requiring expanded production at the relatively low-volume factory for this initial model, so its performance must also be acceptable in Japan. The version sold in the United States is likely to have more power and lower fuel economy, yet it still could achieve better fuel economy than the average U.S. compact by the factors that we assume here.

In the next two paragraphs and in our computations, the estimates do not consider the likelihood of a different hybrid being marketed in the United States. All comparisons in these two paragraphs use the same results of a gasoline vehicle simulation as the basis for the calculations of hybrid fuel consumption savings by driving cycle. Using the estimates prepared for the conventional compact gasoline vehicle (Case 4 of Santini et al., 1999) by the ANL/NREL team, we obtain the following estimates of gallons per hour of fuel consumption for the driving cycles in Japan, Europe, and the United States, respectively: 0.53, 0.70, and 0.92. Here, we assume that the ECE cycle, at 21 mph, causes fuel consumption identical to the U.S. FTP, which is also 21 mph. Breaking out the CAFE values into city and highway, one obtains 0.70 gal/h city and 1.03 gal/h highway. Using the gain factors possible, gal/h*[1-(1/(1+gain))], from Fig. 1 and from Hermance, we estimate gal/h reductions of 0.27, 0.23, and 0.22 for Japan, Europe, and the United States, respectively. Completing the analysis for all possible cycles, using gain estimated from Hermance (1999), and base mpg for the comparable-performance automatic-transmission-equipped conventional vehicle from Santini et al (1999), we obtain the following gal/h reduction potential sequence: NYCC = 0.28; Japan 10/15 = 0.27; ECE and FTP = 0.23; CAFE = 0.22; and U.S. highway = 0.17. Note that these fuel consumption estimates are based on certification tests on dynamometers. As previously noted, and officially acknowledged in the GMG (USDOE, 1997), actual on-road driving results in greater fuel consumption at a given speed. At present, there are only limited Prius test results for on-road driving. The one test by Toyota that could be regarded as on-road driving is labeled "Traffic Jam," and it results in higher gains than those simulated in Santini et al. for the NYCC, which is the same speed (we suspect that it is, in fact, the NYCC, but have not confirmed that at this time). EPA mpg test results for the Prius on the NYCC are 2.2 times the value for the conventional vehicle simulated by Santini et al. This is identical to Toyota's comparison of the Prius and the Carina on the NYCC. For the low-speed Japan 10/15 mode case, we assume that the on-road fuel consumption is identical to test fuel consumption.

The U.S. GMG estimates that on-road fuel consumption in the city (FTP) cycle is 11% more than test fuel consumption. For the highway cycle, it is estimated that the on-road fuel consumption is 28% less. In this analysis, we assume that the applicable on-road adjustment factors for a Prius and a conventional vehicle will be the same, even though the limited test evidence available indicates that the Prius' on-road mpg may deteriorate more relative to the above test results than that for a gasoline vehicle. The adjustment factors adopted are Japan 10/15 = 1.0; ECE = 1.11; FTP = 1.11; CAFE = 1.14; U.S. highway = 1.28. Adjusted gal/h savings values are NYCC = 0.28; Japan 10/15 = 0.27; ECE = 0.26; FTP = 0.26; CAFE = 0.25; U.S. highway = 0.22

While one still sees greater potential to reduce fuel use as average driving speed declines, the differences now look much smaller, if households in the various nations do, in fact, spend about the same amount of time per day in the car. While the gains expressed on a mpg basis vary by a factor of six, these estimated gains on a gal/h basis vary by a factor of only 1.27. Fuel costs become the more important question with regard to relative net present value of consumer benefits from one nation to another and from one driving cycle to another. The incremental cost of the vehicle will be the essentially same regardless of where it is sold, so if its useful life is based on about the same hours of use per year, regardless of location, the net present value of the fuel consumption reductions from use of the vehicle will be closely tied to fuel cost per gallon.

Still, after this calculation, there remains a small benefit to applying this technology selectively to urban driving. For a U.S. consumer, if there can be significant shifts between city and highway driving, increases in fuel savings benefits up to a maximum of 35% are possible. Thus, one might expect multiple vehicle households to choose the hybrid for urban driving when the opportunity presents itself. Further, one might expect those consumers whose mix of driving is more tilted toward city driving to be more likely to buy the vehicle in the first place. Also, we note that the vehicle class under discussion, in the United States at least, is likely to be the commuter car in a typical multiple-car household where it is owned. We suspect that the use pattern of hybrids in the United States will be biased toward urban use and could be as high as 75% urban and 25% highway, instead of the present 63%/37% split.

Other issues are important with respect to household vehicle use. Vehicles that are used at the average rates stated earlier are, on average, used more intensively in the early years of vehicle life than in later years. We based our simulated patterns of use on Table 3.10 in Davis. This is helpful with respect to net present value of fuel savings. We use a 10% rate of discount in our calculations. This, in combination with declining rates of use of the vehicle in later years, means that the net present value of fuel savings in late years of vehicle life is not particularly large.

In the United States, the average life of a vehicle, in miles, is about 130,000 and about 13 years in time. Simulating a vehicle to last that many miles in Japan or Europe, given the annual VMT rates there, leads to a very long vehicle life. Certainly in Japan the implied life seems too long, especially in light of stringent vehicle inspections that tend to get vehicles off the road. Note, however, if we defined life in terms of engine hours of operation, then the vehicles in Japan and Europe would be simulated to last about as many years as in the United States.

Vehicle Characteristics as a Determinant of Owner Behavior

In terms of cost, the hybrid vehicle has one very important distinguishing characteristic from a gasoline vehicle: the battery pack. At present, our estimates have an average household replacing the battery pack once in the vehicle's lifetime. This is less frequent than for electric vehicles. It is quite early in the experience of marketed hybrid vehicles, so the long-term behavior of battery packs remains to be demonstrated. However, it is clear that there is evidence that batteries "like" the nature of hybrid vehicle operation far more than electric vehicle operation. For hybrids, there are many narrow charge discharge cycles, relative to far fewer, wide cycles for electric vehicles. Tests have led to optimism regarding the life of nickel metal hydride packs. Toyota has indicated that a guarantee of a specified life will be provided. However, tests to date are, of necessity, done in a short period. Battery age has been expressed in the technical literature both in terms of "cycle life" (number of charge discharge cycles, a concept proving of little meaning for hybrid batteries) and shelf life. Experiments by Toyota have shown surprisingly good "cycle life" for relatively young batteries.

The information that we have collected indicates that a nickel metal hydride battery will have a shelf life of about six or seven years (Vyas et al., 1997). How its behavior will affect the hybrid vehicle in the last year remains to be seen. In our calculations, we use a shelf life of seven years. It should be acknowledged that there is a glass half empty interpretation above. It is conceivable that there could be a positive discovery that *both* shelf life and cycle life can be extended by hybrid vehicle operating characteristics, and perhaps new strategies. One cautionary note. The latest "Review of the Research Program of the Partnership for a New Generation of Vehicles" (NRC, 1999), on page 39, states that PNGV is enlisting the help of national laboratories to define a generic (nonproprietary) baseline chemistry to show, by example, how to elucidate the failure mechanisms of a system. Developing new electrochemistry is equivalent to starting over in this area." The advantage that Toyota and Honda will have is that they will learn by testing in the field what the failure mechanisms in batteries are, and by doing so, more rapidly solve those battery related problems that have solutions. On the other hand, Toyota may have done the kind of calculations that we report here, and concluded that there is a suitable world market for a hybrid vehicle with existing battery technology, even with seven year pack life. However, the same calculations done for the U.S. will indicate that the vehicle will not represent an economically competitive vehicle for the average U.S. consumer, a PNGV goal. If so, more dramatic successes have to be achieved to meet PNGV goals, but perhaps not to meet Toyota goals.

The question of life of a vehicle in terms of engine hours of operation was raised. Given the operating strategies of hybrids, the more congested the driving conditions, the greater the reduction of engine hours of operation relative to a gasoline vehicle. On the other hand, there will be far more engine starts than for a conventional gasoline vehicle, so the net effect on engine life and reliability is unclear.

Although our reference analysis is for the average household vehicle operator, it is clear that there is a wide distribution of patterns of vehicle use. Some households do drive many more hours than the average. In the event that battery replacement does prove to be a function of shelf life, there might be a tendency for average consumers to shy away from a vehicle with a known pulse in cost after about seven years. We have speculated that lead acid battery packs – much cheaper than nickel metal hydride – might actually see a secondary market in old hybrids utilized at a much lower rate of annual VMT than new ones. In this analysis, however, we assume replacement with nickel metal hydride packs. We do consider the case where high use drivers select the vehicle, knowing that they will wear out the vehicle before shelf life of the battery becomes an issue. We examined a case with hours per day of driving the vehicle at the estimated average speed for that nation, adjusted to cause exhaustion of the battery at an assumed shelf life of seven year, and scrappage of the vehicle just as the shelf life of the battery was exhausted. This type of consumer benefits both by eliminating the need for a battery replacment, and by realizing greater fuels savings per year, sooner, beating the effects of the discount rate.

Another question will be the form of guarantee of battery life. If the guarantee is for a specified number of kilometers - say 100,000 - then the Japanese consumer will have a distinct advantage, since their average speed is lowest, and the rate of accumulation of miles is less for a specified number of hours.

Results and Discussion

Our results are shown in Table 1. We present three sets of three cases each. The gasoline prices specified applied in 1997. The German and Japanese prices are based on exchange rate estimates of regular unleaded relative to U.S. unleaded. The base U.S. price is the average for all grades - \$1.29/gal; the prices for Germany and Japan are \$3.82/gal and \$3.55/gal, respectively. In the first case, battery life is anticipated to be based on either shelf life (seven years) or cumulative mileage (≅ 100,000km), whichever comes first. The U.S. consumer just uses up the mileage on the second battery. The Japanese and German consumers resell the second battery pack for the value of its remaining use. The consumer holds the vehicle until the average annual mileage is reached, which is eleven years in each country. In early years, miles (and hours) per year exceed the average; in later years, usage is less. In the second case, it is assumed that the vehicle is purchased and used exactly seven years, with the rate of use adjusted to exhaust a 100,000-km guarantee on just one battery pack at the end of the seven years, after which the vehicle is scrapped. This seems to make sense only for the Japanese situation. In the U.S. case, this actually requires lowering the utilization rate. In the third case, the vehicle is assumed to last 11 years, as in the first case, but the use rate is adjusted to just cause the second of two battery packs (guaranteed to last 100,000 km each) to wear out. The Japanese case is again most advantageous. This indicates that, if the life of batteries is actually tied to miles driven, the most advantageous use of a hybrid would be in congested urban conditions, where mileage accumulation is slow, and fuel consumption reduction per hour is greatest.

As far as the marketability of the hybrid – vs. the conventional gasoline vehicle – strictly on the basis of NPV economics, there appears to be no long-term, high-volume market in the United States at present fuel prices. The Japanese market appears most attractive of the ones evaluated, but the German market also appears to have the potential to succeed. In either case, the hybrid will compete in the market where the vehicle is driven more hours per day than average. At the fuel and incremental vehicle costs we have estimated, the hybrid does not appear likely to be a universal replacement for the conventional gasoline vehicle in any of the markets examined. Note that the hybrid has to compete with the diesel, a vehicle for which fuel taxes and retail costs have historically been held lower than those for gasoline in Japan and Europe. The position of the hybrid relative to the diesel is a topic for future papers, which are likely to also address the question of emissions. In this paper, consistent with the arguments in Santini et al., we assume no distinction between the emissions of the Prius-like hybrids and conventional gasoline vehicles. However, Hermance (1999) has indicated that the goal of Toyota is to develop an improved version of the Prius for the U.S. market that is very clean, meeting the "super ultra low emissions" vehicle (SULEV) standards of California. States with greatest interest in the hybrid are certainly California, and probably New York, which has attempted to adopt California emissions standards. Both have higher gasoline prices than assumed in Table 1, but not enough higher to make the NPV economics favorable for a household's daily rates of use. Toyota's strategy of placing the Prius in an extremely low emissions category would allow it to market the Prius as a niche vehicle in California and perhaps New York, taking a loss on the Prius, so that other profitable vehicles could be sold, consistent with the California regulations.

Table 1 Long-run, high volume NPV savings (loss) of use of a compact hybrid replacing a compact conventional gasoline vehicle, for selected cases and nations

	Japan			Germany			United States	
Case number	1	2	3	1	2	3	1,3	2
Hours/day driving	1.32	1.75	2.22	1.05	1.16	1.48	1.18	0.92
Savings (gal/h)	0.27	0.27	0.27	0.26	0.26	0.26	0.25	0.25
Gasoline price ($/gal)	$3.41	$3.41	$3.41	$3.70	$3.70	$3.70	$1.29	$1.29
Average speed	14	14	14	21	21	21	27	27
Average annual miles	6740	8945	11340	8070	8890	11340	11400	8905
Years of life	11	7	11	11	7	11	11	7
Year battery replaced	9	not	5	7	not	5	5	not
NPV of fuel savings	$2,950	$2,920	$4,960	$2,470	$2,020	$3,475	$930	$535
NPV of capital cost	$2,520	$2,400	$3,175	$2,770	$2,400	$3,175	$3,175	$2,400
Net savings (loss)	$430	$520	$1,785	($300)	($380)	$300	($2,245)	($1,865)

The vast majority of the difference in fuel cost in the nations examined is the level of fuel tax. Prius type hybrids with our cost estimates cannot be justified on the basis of fuel savings before taxes in any of these countries. The only way that they can provide a return to the consumer is as a mechanism largely for avoiding fuel taxes.

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