Gasoline-Fueled Hybrid vs. Conventional Vehicle Emissions and Fuel Economy

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D. Santini, J. Anderson, J. He, S. Plotkin, and A. Vyas
Argonne National Laboratory, 9700 S. Cass Ave., Argonne, Illinois 60439

D. Bharathan
National Renewable Energy laboratory, Cole Boulevard, Golden, Colorado 80401

ABSTRACT

This paper addresses the relative fuel economy and emissions behavior, both measured and modeled, of technically comparable, contemporary hybrid and conventional vehicles fueled by gasoline, in terms of different driving cycles. Criteria pollutants (hydrocarbons, carbon monoxide, and nitrogen oxides) are discussed, and the potential emissions benefits of designing hybrids for grid connection are briefly considered.

In 1997, Toyota estimated that their grid-independent hybrid vehicle would obtain twice the fuel economy of a comparable conventional vehicle on the Japan 10/15 mode driving cycle. This initial result, as well as the fuel economy level (66 mpg), made its way into the U.S. press. Criteria emissions amounting to one-tenth of Japanese standards were cited, and some have interpreted these results to suggest that the grid-independent hybrid can reduce criteria emissions in the U.S. more sharply than can a conventional gasoline vehicle. This paper shows that the potential of contemporary grid-independent hybrid vehicle technology for reducing emissions and fuel consumption under U.S. driving conditions is less than some have inferred. The importance (and difficulty) of doing test and model assessments with comparable driving cycles, comparable emissions control technology, and comparable performance capabilities is emphasized.

Compared with comparable-technology conventional vehicles, grid-independent hybrids appear to have no clear criteria pollutant benefits (or disbenefits). (Such benefits are clearly possible with grid-connectable hybrids operating in zero emissions mode.) However, significant reductions in greenhouse gas emissions (i.e., fuel consumption) are possible with hybrid vehicles when they are used to best advantage.

INTRODUCTION

The hybrid vehicle is about to be introduced into the United States: Toyota (San Jose Mercury News, Oct. 1998) and Honda (North American International Auto Show, Jan. 1999) have announced their plans. Moreover, General Motors has announced that the “future generation EV1 would be a hybrid, getting 60 mpg on reformulated gasoline” and that GM “hopes to be selling hybrid EV1s by 2001” (Llanos 1998). Therefore, it is timely to compare the fuel economy and emissions performance of such hybrids with those of conventional vehicles.

The changes in hybrid vehicle fuel economy as one goes from highway driving to suburban driving and to congested center city driving are far different from those for conventional gasoline
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vehicles. Fuel economy over this sequence may actually increase for a hybrid, while it deteriorates sharply in conventional gasoline vehicles. Hybrid vehicle technology promises to provide the next large incremental leap in fuel economy, should that leap be deemed necessary. One of the three major goals of the Partnership for a New Generation of Vehicles (PNGV) is to develop an affordable mid-size passenger car with triple the fuel economy of mid-1990s mid-size vehicles (the 3X vehicle). PNGV participants consider “hybridization” to be among the likely components of the technological package needed to accomplish this goal.

Two key PNGV vehicle performance goals have dictated our computer simulation of hybrid designs to date. These are (1) the ability to maintain a steady 55 mph for 20 minutes up a 6.5% grade, with a load of six passengers and a full trunk of luggage; and (2) the ability to accelerate from 0 to 60 mph in 12 seconds, with two passengers on board and no luggage. For the hybrid, we add the qualifier that the vehicle must be able to do the 0-60 mph acceleration when the battery pack is at a 20% state-of-charge (SOC). This means that the hybrid will be able to accelerate faster when the SOC exceeds 20%, so long as the motor is large enough to take advantage of any excess power available. Hybrid vehicle marketers should size motors to take advantage of the battery pack’s capabilities at higher SOCs, where the vehicle will typically operate.

Over the past two years, the Argonne study team has been using the Advanced Vehicle Simulator (ADVISOR), a computer model developed at the National Renewable Energy Laboratory, to study the problem of developing “performance-comparable” comparisons of conventional and hybrid vehicles. The Argonne researchers provide feedback to NREL ADVISOR programmers; NREL’s D. Bharathan has joined the study team, thereby increasing the value of this feedback. We used a slightly different version of ADVISOR from that provided on the Internet when the calculations for this paper were made; the features we used are to be incorporated into an updated version.

The U.S. Environmental Protection Agency (EPA) has carefully tested and evaluated the Toyota Prius (Hellman, Peralta, and Piotrowski 1998), allowing us to benchmark the use of ADVISOR as we explore the potential for understanding offered by the computer comparisons. The hybrid designs we are otherwise evaluating use PNGV (or better) performance goals for continuous steady speed on a specified grade and for 0-60 acceleration time. The tested Prius does not meet even the least stringent of these goals. (Most vehicles sold today accelerate to 60 mph in well under the PNGV goal of 12 seconds and can continuously climb grades well in excess of the PNGV 6.5% goal.)

BACKGROUND

The regulation of motor vehicle emissions in the United States has evolved considerably since the 1960s. In the 1970s, the Federal Test Procedure (FTP @ 19.5 mph) was developed for emissions certification and fuel economy testing, and the Highway Fuel Economy test (HFET @ 48.2 mph) was developed for fuel economy testing. The Corporate Average Fuel Economy (CAFE) regulations are based on data from the two tests. Because vehicles did not behave on the road as they did in these tests, additional tests and test equipment were developed, and adjustment factors were added to discount the fuel economy estimates printed on vehicle stickers.

In this paper, we examine the fuel economy and emissions behavior of hybrid vehicles, particularly those for one of the first entrants, the Toyota Prius. Some of the same problems associated with
gasoline-vehicle test results (such as the initially published results not matching on-road performance) are already evident in the case of the Prius. The discrepancies are being revealed more rapidly this time around, and certain new twists have arisen. We have applied computer models to the problem of comparing the new hybrid technology with present-day gasoline-vehicle technology. The Prius provides a first opportunity to compare preliminary computer simulations with a tested commercial product to calibrate and evaluate the computer model. For this comparison, we make use of several old and new driving cycle test results.

In the last decade, to better explain emissions and reasons for fuel economy “discounts” in real-world driving, additional driving cycles were developed. To reflect vehicle emissions behavior on hot summer days that are conducive to ozone formation, EPA developed the SC03 driving cycle and test, which is to be done at 95° F rather than the 70° F for the FTP, HFET, and all other U.S. tests discussed in this paper; a specified humidity level is also part of the SC03 test. This test averages about 22 mph. The REP05 cycle (51.5 mph) simulates higher top speeds and accelerations than those in the HFET, including a long segment simulating urban freeway driving at speeds over 70 mph. Another new cycle, the US06 cycle, has an average speed that is almost the same as the HFET, but it is far more aggressive in terms of acceleration and deceleration rates. At the other end of the speed scale, the New York City cycle (NYCC) is a choppy, low-average-speed (about 7.1 mph) cycle with many stops. Emissions in the FTP, SC03, and US06 tests will soon count toward the certifiability of emissions rates for motor vehicles. For fuel economy, the FTP and HFET will remain the basis of certification.

To determine CAFE fuel economy, the fuel consumption of the FTP is weighted at 55%, and that for the HFET, at 45%. In the 1970s, when the test was developed, the Federal Highway Administration estimated that 55% of U.S. passenger car VMT was urban. Today the figure is closer to 65% (Teets 1997), as urbanization of the U.S. population increases and people use air travel more for long trips.

HYBRID VEHICLES

The generic term “hybrid vehicle” signifies a type of vehicle that uses both an internal combustion engine and an electric motor (and generator), a battery pack, and regenerative braking. Vehicle configurations are described as “series” or “parallel.” In the series configuration, the engine powers a generator, which powers a motor (or motors) and charges a battery (which in turn powers motors to supplement engine generator power), with only the motor(s) finally driving the wheels. In the parallel configuration, both the engine and one or more electric motors (using a battery previously charged by engine-generated electricity) mechanically power the wheels. The most important differences between a hybrid vehicle and a conventional vehicle are that (1) the hybrid can essentially eliminate fuel waste during idling (when a vehicle is at a stop or decelerating) and (2) through regenerative braking, it can retrieve kinetic energy during deceleration. The hybrid’s engine also runs within a narrower, more efficient range of operating points than in a conventional vehicle. Toyota (1997) estimated that the Toyota Prius obtained a 100% increase in fuel economy compared to a Japanese Toyota Corolla. Hermance (1998), in supplemental comments, indicated that the Prius got 20% of its increase via regenerative braking, 40% by elimination of low-load/no-load engine operation (such as idle), and 40% by using a more efficient Atkinson cycle engine. [Note that this allocation is both driving-cycle-specific (for the Japan 10/55-mode cycle) and Prius-specific.] The goal is to have the engine operate only when it
provides greater efficiency than the battery and motor, and to have the battery and motor operate when they provide greater net efficiency. In practice, such operational considerations as maintenance of battery charge within a desired range or transmission type and gear selection may prevent realization of the ideal.

At idle, an engine’s efficiency is zero, but this is not the whole story. Two engines with different idle fuel flow rates (e.g., a spark ignited vs. a compression ignition engine) both have zero efficiency at idle. However, the one with the higher fuel flow rate obtains the greater benefit from elimination of idle. Typically, the hybrid is designed to turn off the engine when the vehicle is decelerating or stopped. This is the stated procedure for the Toyota Prius (observable on a dashboard screen showing real-time energy flows). In recent tests of the Prius, the EPA noted that “27-31 engine starts were noted over the cold start LA-4 cycle” (Hellman, Peralta, and Piotrowski, p. 30). In addition to the fuel flow savings during idle and deceleration, the hybrid can also eliminate a large share of the low-load/low-efficiency engine operating points.

Elimination of idle fuel flow and retrieval of kinetic energy by regenerative braking are of little or no value during steady-state cruising. The more stops and acceleration/deceleration cycles and the longer the duration of stops in a cycle, the more hybridization can improve a vehicle’s fuel economy. A probable side effect of hybridization, with batteries used for energy storage, is increased vehicle mass. Mass increases tend to offset the benefits of hybridization, but not in the same manner as for conventional vehicles, due to regenerative braking. For a given state of engine design, though, there is likely to be little or no benefit on the highway from hybridization.

It is possible to alter the hybrid’s engine size and/or design in such a way that the efficiency of the engine during highway cruising can be improved. We view this as a secondary effect: gear ratios can be selected in a conventional vehicle in such a way as to cause the engine load during highway cruising to be at or near the optimum efficiency of the engine. However, the effect should be of more value if hybridizing high-performance vehicles.

The operating efficiency of the engine can be limited by the transmission gearing at low rpm. A continuously variable transmission (CVT) can increase the gear ratio at low rpm beyond what is acceptable in a normal transmission, thereby moving the torque point up at low rpm. This also can be done electronically in a series hybrid. This allows the engine to operate more efficiently. CVTs in conventional vehicles have the same advantage for low-load operation, but at a cost of lower overall efficiency at high load than for a manual transmission or for an automatic transmission with a “lock-up” feature.

In our hybrid vehicle evaluations, we examine only charge-sustaining hybrids capable of being driven without grid charging. However, we are also evaluating grid-connectable hybrids designed to meet the same performance standards (meet or exceed the PNGV requirements) as grid-independent hybrids. These grid-connectable hybrids use batteries designed to have a ratio of power to energy between that of a Prius battery and a Toyota RAV4 EV battery. They generally can be driven about 20-30 miles in all-electric mode when charged to 95% SOC and depleted to 20% SOC. At this point, if the vehicle has not stopped for electric recharging, it would start its engine, recharge the battery to an intermediate SOC, and operate identically to a grid-independent hybrid. We present no analysis here for such hybrids, but we note that there are emissions trade-offs that must be understood.
EMISSIONS CONSIDERATIONS FOR HYBRID VEHICLES

Emissions trade-offs for hybrid vs. conventional vehicles with essentially the same emissions control system technology are thought to be as follows:

1. The hybrid will have more engine starts. A hybrid with a large battery pack in low-speed driving cycles, where the vehicle can operate exclusively on battery power for several minutes between engine restarts, may have the worst emissions; catalyst cool-down between starts could mean high restart emissions. Because hybrids with small battery packs (such as the Prius) are likely to have frequent starts, with the catalyst remaining hot, they may not have an engine restart problem.

2. The hybrid engine starts at higher rpm and brake mean effective pressure (bmep, an alternate measure of “torque”) and does not idle. During warm-up, it has a higher fuel flow rate than a conventional vehicle and therefore warms up faster. The Toyota Prius engine is designed to stay on until the catalyst reaches light-off temperature. The real-world effects of this need to be studied: although the engine and catalyst will warm up sooner, the engine will also burn far more fuel (and pass more pollution through) while the catalyst is cold. We later show (Table 2) that the net effect seems to result in similar “bag 1” cold start emissions in the FTP. [All emissions cycle tests presented here, aside from bag 1 of the FTP and the FTP itself, are either hot-started or hot-stabilized (the emissions collection bag is changed while the engine is running and is hot or hot-started). The Japan10/15 mode cycle is hot-started (Walsh 1998).]

3. Once warm, the hybrid engine (or “power unit”) should operate with no sharp load transients, in a region where the catalyst is highly efficient and engine-out emissions are low. In our simulations, the engine is “load following,” changing load based on average prior changes in load over several seconds.

4. If an engine of a given technology and displacement is designed to run rich at high load, with attendant catalyst inefficiencies, then the hybrid vehicle operation for this same engine (derated to run only below the loads and rpm levels where enrichment was previously used) should reduce enrichment emissions effects very sharply, because the motor and battery provide incremental high load power. The Toyota Prius engine is no smaller in displacement than the engine in the competing gasoline-fueled Toyota Corolla (both at 1.5 liters), but the Prius’s maximum rpm is only 4000 (compared to 5000+ for the competing engine). Quite often, in the 4000 rpm to max rpm range, normal gasoline engines run “rich” and have significantly higher tailpipe emissions of HC and CO per unit of power delivered (An 1997). If displacement is the criterion for engine size, then the Prius engine is not downsized; if power is the criterion, then it is.

In Auto/Oil Technical Report 19 (1996), Table 4 shows, for an average of six gasoline vehicles, the effects on g/mi emissions of the very aggressive, high-speed “hot-stabilized” (hot engine, no start) REP05 cycle vs. the hot-stabilized bag 2 of the FTP. CO emissions rise far more rapidly than HC or NOx when the high load operation of the REP05 cycle is imposed on the engine (HC and NOx did rise considerably relative to bag 2 hot-stabilized emissions, but negligibly compared to hot-start bag 3 emissions). In fact, for any of the bags of the FTP or the entire FTP, the ratio of REP05 emissions to FTP emissions is highest for CO. As another example, F. An et al. (1997) designed an aggressive high-load/high-speed driving cycle that has even stronger effects than the REP05 cycle in terms of inducing enrichment. Comparing the increases in CO, HC, and NOx for
this cycle relative to the FTP, one sees the same result. If hybridization could eliminate enrichment in hot-stabilized conditions, it could preferentially reduce CO emissions, at least from present-technology engines. The Prius does appear to preferentially reduce CO emissions, but this may be largely a result of reducing the time of enrichment during cold starts.

**An Emissions Estimation Fable.** Cold starts are the major problem in conventional vehicles. Episodic ozone control programs cited as good examples by the EPA include efforts to reduce cold starts and refueling during daytime hours (EPA 1998). A grid-connectable hybrid charged overnight and operating in all-electric mode would do both. EPA tests of the grid-independent Prius hybrid by Hellman, Peralta, and Piotrowski (1998) show that cold starts are the single largest contributor to its FTP emissions, as in conventional vehicles.

For a conventional gasoline vehicle, hot starts after the ten-minute soak period in the FTP (see Auto/Oil Technical Bulletin 19, Figure 8) also produce a noticeable pulse in emissions, comparable with those from enrichment events in REP05 and larger than any other FTP increment after catalyst warm-up. Hot restart emissions from a hybrid are not necessarily trivial, especially if there is a long time between starts. The higher the battery pack’s energy storage capability (at a given level of peak power), the fewer stop-start cycles there will be, and the longer the interval between starts. A grid-connectable hybrid with the same performance as a grid-independent hybrid would have fewer stop-start cycles, longer cool down between starts, and higher hot restart emissions when operating in a grid-independent mode. Therefore, the grid-connectable hybrid, if tested by EPA under a test protocol as if it were a grid-independent hybrid, would probably have higher emissions than a true grid-independent hybrid.

However, the grid-connectable hybrid can operate in zero-emissions mode in the morning and early afternoon, if not the whole day, when fully charged the night before. For the 20+ mile EV-mode-capable hybrid departing a metropolitan area in zero-emissions mode (until reaching 20% SOC), most of the urban airshed share of vehicle miles of travel (VMT) would be in electric operation. If the future EPA Mobile model’s simulation of this vehicle type’s behavior were programmed to allow an air quality control region to opt for required electric-mode operation on ozone action days, then the vehicle would be estimated to have on-road emissions far lower than its grid-independent counterpart.

Suppose that (1) the grid-connectable hybrid were sold to an owner with no charging facility; (2) the urban area adopted an inspection system, enforced by infrared heat signature monitors, with heavy penalties for ozone day operation of grid-connectable hybrids in hybrid mode instead of electric mode; and (3) aftermarket or OEM designers developed a mechanism for remote control of the engine, allowing it to be turned on for overnight self-charging of the hybrid to 95% SOC. The metro area could also have a remote control capability to make these grid-connectable vehicles, parked at the proper geopositioned coordinates, self-charge overnight.

The point of this parable of a possible future, is this: In the late 1960s, we did not know how the gasoline vehicle’s emissions would be controlled, and now we are in a similar situation relative to hybrid vehicle emissions. We are at the earliest stages with a very new technology, one not yet even introduced in the United States. The EPA is considering how to test it for certification as if it were a gasoline vehicle — a daunting and probably undesirable task. If the technology is successful, it will be necessary to develop an understanding of the real-world behavior of this class of vehicle, as consumers decide how best to use it. We speculate here on one possible sequence of
events and control technology, but at this point we can only speculate, not predict.

FUEL ECONOMY AND USE OF THE HYBRID

While the hybrid will have a better fuel economy advantage relative to gasoline vehicles in city driving than in highway driving, this advantage will be even greater in the most congested driving conditions — conditions found in other industrialized nations that also have much higher fuel prices. Although our cost analyses imply that hybrid vehicles will not pay for themselves in fuel savings in this country, they are likely to be cost-effective elsewhere, and therefore their development path is likely to continue. The United States may find itself importing many such vehicles in the future if an oil price crisis like that of the 1970s and early 1980s occurs. In the meantime, some hybrids will enter the domestic market, and consumers will become familiar with them. It seems logical that in multiple-vehicle households, they will be selectively used where their advantages lie, but this remains to be proven by experience. To assume, as present CAFE rules do, that these vehicles will be driven for 55% of their VMT in city driving and 45% in highway driving (according to present FTP and HFET tests) would be a mistake. How then do we rate these vehicles?

The EPA’s “Voluntary Mobile Emissions Program” (VMEP) allows a small portion of emissions credits to be generated by new and creative programs, so long as those programs are quantified (EPA 1997). Perhaps an equivalent set-aside could be developed for fuel economy rating of new vehicle technologies, such as hybrids. A portion of CAFE credits could be granted flexibly for new vehicle technology, so long as the manufacturer demonstrates to EPA how the technology provides real savings (of greenhouse gas emissions and oil use). If the technology succeeded and all claimed credits were used up, the manufacturer(s) and EPA would be required to develop new official certification methods for the technology. Otherwise, issues of proper rating and testing are largely moot.

TESTING AND MODELING HYBRIDS: A STATUS REPORT

Toyota tested the Prius hybrid on the Japan 10/15 mode driving cycle; 66 mpg was realized for this cycle, twice the fuel economy of a comparable gasoline model on this cycle [Toyota 1997, p. 12; Hellman, Peralta, and Piotrowski 1998 (hereafter, “HPP”), p. 53]. The vehicle’s emissions were also tested on this cycle and estimated to be “about one tenth” of the Japanese standard for CO, HC, and NOx (Toyota 1997, p. 12). Table 1 shows the emissions estimated by Toyota for the Prius on the Japan 10/15 mode cycle, in comparison to the standards and to the most similar test conducted in the U.S. (bag 2 of the Federal Test Procedure). The Japan 10/15 mode cycle is a “hot-start” test that averages 14 mph, while bag 2 is a hot-stabilized test that averages 16 mph. Emissions results for three 1998 model year vehicles are also provided. The Toyota test results for emissions and fuel economy on the Japan 10/15 mode cycle are probably reproducible. U.S. gasoline vehicles can obtain emissions far below the Japanese 10/15 mode standards, so this is not a remarkable result.
Table 1 Test Results: Conventional Cars vs. Toyota Prius for Similar Driving Cycles

<table>
<thead>
<tr>
<th>Vehicle and Test Type</th>
<th>HC</th>
<th>NOx</th>
<th>CO</th>
<th>MPG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Japan 10/15 standards (g/mi)</td>
<td>0.4</td>
<td>0.4</td>
<td>3.4</td>
<td>n/a</td>
</tr>
<tr>
<td>Toyota Prius on Japan 10/15</td>
<td>0.03</td>
<td>0.03</td>
<td>0.13</td>
<td>66</td>
</tr>
<tr>
<td>EPA - Prius on FTP Bag 2</td>
<td>0.01</td>
<td>0.03-0.04</td>
<td>0.1-0.2</td>
<td>59-67 (57*)</td>
</tr>
<tr>
<td>1998 Cavalier on FTP Bag 2</td>
<td>0.012</td>
<td>0.013</td>
<td>0.28</td>
<td>n/a</td>
</tr>
<tr>
<td>1998 Contour on FTP Bag 2</td>
<td>0.015</td>
<td>0.060</td>
<td>0.31</td>
<td>n/a</td>
</tr>
<tr>
<td>1998 Crown Victoria on FTP Bag 2</td>
<td>0.002</td>
<td>0.001</td>
<td>0.21</td>
<td>n/a</td>
</tr>
</tbody>
</table>

* Value based on statistical fit of the type used by HPP to adjust for change in SOC of battery during test. *57 mpg assumes no change.

FUEL ECONOMY

"Undiscounted" Dynamometer Test Results: Fuel Economy. Information about the Toyota Prius made its way into the popular press, without qualification. A December 15, 1997, Business Week article reported the 66 mpg value. The “San Jose Mercury News,” MSNBC (Llanos 1998), “Detroit Free Press” (Hazelton 1998), “Lexington Herald Leader” (Butters 1998), and other news providers quoted the 66 mpg figure. The SAE published Toyota’s results in July 1997, noting that they applied to Japan but providing no guidance on what might be obtained in U.S. driving conditions (Yamaguchi 1998). After Toyota decided to bring the vehicle to the U.S., test numbers on U.S. driving cycles began to be provided. K.G. Duleep was told that the number would be essentially the same on the city and highway driving cycles, about 54 mpg. Santini and Vyas used this value in a May 1998 evaluation. At this meeting, D. Hermance, in comments supplemental to his presentation material, indicated that the Prius “unofficially” would likely obtain fuel economy close to the number that Duleep had mentioned.

In August, HPP published the EPA test results. These extremely thorough tests show that measuring the fuel economy and emissions of the Prius (and, most likely, any other hybrid) is a tricky matter. Under the standard sequence of tests, including the HFET, they estimated an HFET rating of about 50 mpg; under another, nonstandard sequence of ten repetitions of only the HFET, they estimated about 54 mpg.

HPP conducted several tests in which they began with the Prius battery deeply discharged, then repeated multiple tests as the Prius returned to normal hybrid operating mode. Such a condition could occur on a long trip for a grid-connected hybrid. Suppose, for example, procedure on an ozone action day would be to discharge the hybrid battery to 20% SOC, and the subsequent hybrid operation strategy on those days would be to have the vehicle operate in a 40-60% SOC "window." Then the first start of the engine would involve running long enough to change the charge from 20% to 60%. Thereafter, engine-on operation would be long enough only to change the charge from 40% to 60%.

The HPP tests starting with a discharged battery show that gram per mile emissions and fuel consumption would be higher during the time that depleted charge was made up. For the first of
four LA-4 test cycles following battery pack discharge, the fuel economy of the Prius was 44 mpg, rising to 50 mpg in the last two cycles. NOx and NMHC emissions per mile were about double in the first cycle; CO emissions were no different.

By September 1998, after the EPA report, the press report mpg values dropped. Askari (1998) titled her article “Hybrid Toyota: Clean, 50 mpg.” In October, the Chicago Tribune reported the EPA’s undiscounted values, at least in one location.

"Discounted" and Field Results: Fuel Economy. Bedard (1999) implied there is an EPA city driving rating of 43 mpg and a highway rating of 41 mpg (p. 68). Using the Gas Mileage Guide (DOE, various years) discount factors of 10% for city mpg and 22% for highway mpg, we can “back out” implied test ratings of 48 mpg city and 53 mpg highway, values consistent with the EPA undiscounted test. The question of proper discount factors for hybrids should be regarded as highly speculative until many vehicles are on the market and systematic studies of their in-use fuel economy have been completed.

Bedard provided Car and Driver’s observed fuel economy of 35 mpg for the Prius, well below its presumed EPA ratings of 43 mpg city and 41 mpg highway. We estimated a 34.3 zero net charge/discharge mpg rating statistically from the HPP results on the SC03 cycle, and we estimated a 35.6 zero net charge/discharge rating from the six HPP results on the US06 cycle. (Clearly, a 35 mpg “on-road” fuel economy is not out of the question for this vehicle if it is driven aggressively.) Other writers who tested the Prius did better than Car and Driver. Wolfkill (1998), driving in Seattle, Wash., achieved over 40 mpg in the city. Hornbostel (1998), driving in Japan, indicated that his family’s Prius got about 45-50 mpg, consistent with the expectation that fuel economy would be better (in light of test and simulation results here) under Japanese driving conditions. An HPP graph presents results of a test (or tests) on the NYCC that show the Prius obtaining a bit more than 30 mpg. The value cited by Hornbostel implies that if the Japanese were to develop a discount factor relative to the Japan 10/15 mode cycle for the Prius in their “city” driving, it should be considerably larger than the U.S. 10% discount factor for city driving (perhaps 24 to 32%). Argonne’s experience with the on-road mpg of the Prius is similar to that of Wolfkill.

EMISSIONS

Wang et al. (1997) have reported simulation results with early versions of ADVISOR, and Argonne staff have repeated comparative simulations with more recent versions. Emissions results obtained to date are more in the nature of calibration results than prediction results. We have conducted two sets of comparisons to date, with two very different versions of ADVISOR; results should not be regarded as definitive.

Argonne Simulations, Dec. 1997. Wang et al. (1997) compared an aluminum-intensive conventional vehicle, with an engine (Mitsubishi 1.8-L, DOHC 4V) that included enrichment at high rpm, to a grid-independent series hybrid with the same engine. The hybrid used a thermostat operating strategy that kept it from operating in enriched mode when hot. The thermostat strategy turns the engine on and off at one set point, which had to be varied by driving cycle. In this study, we added a cold start to each of the four driving cycles examined (NYCC, FTP, HFET, and REP05), to simulate real-world driving, and repeated the cycle until 30 minutes had expired. Percentage changes cited are for the hybrid in comparison to the conventional vehicle, on the same driving cycle. The grid-independent hybrid had consistently higher NOx emissions. NOx was
almost the same on the REP05 cycle, about double on the FTP and HFET, and triple on the NYCC cycle. VOC (HC) was lower in three of the four cycles simulated, and CO was higher in three out of four (more than double in two cases).

Of the four cycles, only the REP05 cycle had the ability to make the conventional vehicle’s engine operate in the high rpm, enriched region. In the hybrid, this did not happen. In the simulation, the HC, NOx, and CO emissions in the REP05 cycle all exceeded those in the HFET for the conventional vehicle, while for the hybrid all three were lower. HC and CO emissions for the hybrid were lower in the REP05 cycle than for the conventional vehicle, and NOx emissions were essentially identical. The single largest decline for any pollutant (35%) was for CO in the REP05 cycle, consistent with earlier arguments about the effects of eliminating hot-stabilized enrichment via hybridization.

Wang et al. noted that “the ‘early on the learning curve’ modeling used to characterize these vehicles indicates that they do not exhibit the large emissions reductions widely predicted for hybrids.” They also noted emissions benefits from fuel economy improvement. Reductions in particulate emissions and sulfur oxide emissions were estimated as a function of fuel consumption. Also in that study, fuel cycle emissions reduction benefits for all five pollutants were demonstrated as a function of the relative fuel economy of the vehicles in the specified driving cycle.

Argonne/NREL Simulations, Dec. 1998. The ADVISOR model now allows the use of an automated “load-following” engine control strategy. Recent experiments have focused on ensuring the accuracy of fuel economy estimates for “performance equivalent” hybrids and conventional vehicles. For comparable moderate-performance simulations, for the FTP only, the latest estimates indicate that a parallel hybrid with comparable emissions control system characteristics would have emissions increases of 30% for HC, 24% for CO, and 67% for NOx. A series hybrid with comparable emissions control system characteristics would have increases of 12% for HC, 9% for CO, and 40% for NOx, slightly less than the parallel hybrid. The average absolute percentage difference between the series hybrid vehicle and conventional vehicle emissions for the FTP was about half that in the 1997 tests (27%), although emissions from the hybrid were consistently higher than those from the conventional vehicle. The parallel hybrid’s FTP emissions were estimated at an average of 16% over those of the series hybrid. (The Prius is said to combine the features of series and parallel hybrids.)

At this point, ADVISOR provides no evidence of reliably measurable differences in emissions between comparable-performance conventional and hybrid vehicles that share the same emissions control technology. Emissions control systems specifications have been derived from control system behavior for technology developed for gasoline vehicles, not specifically for hybrids.

Emission Test Results. The preliminary modeling results contrast with Toyota’s statement that “compared to conventional gasoline-powered passenger vehicles, THS vehicles emit about half as much CO2 and about one-tenth [italics ours] as much CO, HC, and NOx” (Toyota, p. 12). The EPA’s HPP report compares emissions results for the Prius with those for the Toyota Corolla and the Suzuki Metro. (By EPA classifications, the Metro and the Prius are both “subcompacts.” The Prius crosses the “compact/subcompact” interior-volume boundary because of trunk size, due to the battery pack, rather than passenger compartment size. Consumers would likely see the Prius as a competitor with compact-size cars.)

The Prius had from 25% (NOx) to 67% higher emissions than the Metro and from 58% (CO and
NOx) to 67% (HC) lower emissions than the Corolla. Actual emissions values for the Prius were 0.06 g/mi for nonmethane hydrocarbons (NMHC), 0.5 g/mi for CO, and 0.05 g/mi for NOx. The Prius certainly did not test at one tenth the emissions of these competing conventional gasoline vehicles. However, it met the California Air Resources Board (CARB) present and planned Low Emissions Vehicle (LEV) category (CARB 1998a), and it probably could be upgraded to the present and future Ultra Low Emissions Vehicle (ULEV) category by means of added hydrocarbon control.

In 1997, CARB defined emissions for six clean, automatic-transmission-equipped vehicles. Five of the six had four-cylinder engines ranging in displacement from 1.8 to 2.4 liters; the sixth was a 4.6-liter six-cylinder vehicle: all larger than the Prius’s engine. Low-mileage nonmethane organic gas (NMOG) emissions were less than or equal to the Prius’s HC emissions in four of the six cases and 20% higher in two. CO emissions were as much as 260% higher (lower in only one case). All six vehicles had NOx emissions as low as or lower than the Prius. In 1998, CARB (1998b) reported on experiments in which it installed advanced catalysts on 1997 and 1998 model year mid-size vehicles with engines from 2.3 to 5.0 liters in size. Both NMHC and NOx emissions of the four mid-size vehicles were less than those of the Prius, while CO emissions ranged from about equal to twice as high. The Prius hybrid’s CO emissions were clearly lower relative to these gasoline vehicles’ CO emissions, but its HC and NOx emissions were little less, if at all.

In Table 2, we compare the average emissions in the FTP Bag 1, Bag 2, and Bag 3, as well as the total weighted cycle emissions, for three 1998 model year gasoline vehicles selected for reasons other than their low emissions (Santini and Saricks 1998). The emissions pattern among the bags is similar for the Prius and the conventional gasoline vehicles. Again, the pollutant that appears likely to be reduced significantly by hybridization (if the Prius results can be generalized) is CO.

### Table 2 EPA Test Emissions for Prius vs. Mean for Three 1998 Passenger Cars

<table>
<thead>
<tr>
<th></th>
<th>Bag 1</th>
<th>Bag 2</th>
<th>Bag 3</th>
<th>Total Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>NMHC</td>
<td>3-Car Mean</td>
<td>0.29</td>
<td>0.01</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>Prius</td>
<td>0.20#</td>
<td>0.01^</td>
<td>0.04^</td>
</tr>
<tr>
<td>NOx</td>
<td>3-Car Mean</td>
<td>0.23</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>Prius</td>
<td>0.15#</td>
<td>0.04^</td>
<td>0.07^</td>
</tr>
<tr>
<td>CO</td>
<td>3-Car Mean</td>
<td>4.85</td>
<td>0.33</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>Prius</td>
<td>1.00#</td>
<td>0.15^</td>
<td>0.50^</td>
</tr>
</tbody>
</table>

# Mean of last two tests in Table 1, HPP.
^ Mean of four tests in HPP, Table 13 for Bag 2 and Table 14 for Bag 3.
* From Table 25, HPP (1998).

Although those familiar with the process of ozone formation commonly focus only on HC and NOx, CO is actually an ozone precursor. T.J. Lareau (1994) provides an example of accounting for the effects of CO; this study, in turn, uses a formula used by Sierra Research (1991). We explore the implications of the Sierra Research formula, VOC + NOx + CO/7, for weighting the contribution of these pollutants to ozone formation. On the basis of the Prius reductions in Table 2, the weights would be 0.01 for NMHC, 0.02 for NOx, and 0.13 for CO. At the levels of control now achieved in gasoline vehicles, the most valuable reductions in ozone precursor emissions for a grid-independent hybrid might prove to be CO, a possibility that deserves attention in future...
analyses.

It appears that without the ability to operate in all-electric mode, hybridization does not guarantee lower vehicle emissions than those of competing gasoline vehicles, at an approximately constant level of emission control technology. However, once the vehicle itself is as “clean” as a ULEV vehicle, then the rest of the fuel cycle emissions for HC and NOx become more important than the vehicle tailpipe emissions (see Wang et al. 1997 for upstream emissions estimates). At that point, the fuel economy of the ULEV vehicle, or its ability to use clean electric power, is more important than further tailpipe emissions reductions.

MODEL VS. TEST RESULTS

Using the ADVISOR Model for Fuel Economy Sensitivity Analysis

We compare ADVISOR results for a “Prius-like” parallel hybrid with the EPA test results for the Prius. The Prius, with its sophisticated (possibly proprietary) transmission, is termed a “series-parallel” hybrid by Toyota. The ADVISOR model version used here (NREL, October 1998) has one parallel hybrid configuration, which cannot be expected to exactly mimic the Prius configuration. (At this writing, the National Renewable Energy Laboratory’s ADVISOR model was available to Argonne in “beta” test format. Thus, our results are illustrative rather than definitive.)

With U.S. Department of Energy support, Argonne National Laboratory is setting up test facilities to evaluate the Prius and other hybrids under present and potential U.S. driving conditions. Second-by-second behavior of components, fuel consumption, and emissions will be evaluated once the facility has been completed and “benchmarked.” While this was not possible with EPA test equipment, the thorough tests that EPA was able to do show that test procedures and equipment specific to hybrids need to be developed. The dynamometer used had only a single roll, with braking of the vehicle occurring only through the drive wheels; this should have provided a slight, unwarranted fuel economy advantage for the Prius by increasing regeneration, but the precise magnitude of the effect cannot be quantified. It is likely that this aspect of the testing procedure also affected Toyota’s results, contributing to the high fuel economy estimate for the Prius.

Prius data were collected from the literature and from interviews with Toyota staff (Duleep 1998). Table 3 gives estimates of tire rolling resistance, frontal area, coefficient of drag, vehicle mass, and test mass for the vehicles simulated by ADVISOR and from the EPA tests.

Figure 1 shows the simulated power profile of the nickel metal-hydride battery pack used in the Prius simulations, as a function of SOC. A pseudo-Atkinson-cycle engine map was developed, assuming that the unlabeled engine map in the Toyota Prius brochure accurately reflected the shape of the peak torque curve and the brake specific fuel consumption (BSFC) “pattern.” F. An estimated the peak efficiency of the pseudo-Atkinson-cycle engine on the basis of literature data and a theoretical approach he had developed.
### Table 3 Characteristics of Four Simulated Vehicles and Prius as Tested by EPA

<table>
<thead>
<tr>
<th>Parameters</th>
<th>EPA Test</th>
<th>ADVISOR Simulations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Case 1:</td>
<td>Case 2:</td>
</tr>
<tr>
<td></td>
<td>Prius by EPA</td>
<td>&quot;Prius&quot;</td>
</tr>
<tr>
<td>Curb weight (kg)</td>
<td>1265</td>
<td>1267</td>
</tr>
<tr>
<td>Test load (kg)</td>
<td>59</td>
<td>136</td>
</tr>
<tr>
<td>Test mass (kg)</td>
<td>1364</td>
<td>1403</td>
</tr>
<tr>
<td>Frontal area (m²)</td>
<td>Not given</td>
<td>2.15</td>
</tr>
<tr>
<td>Coefficient of drag (Cd)</td>
<td>Not given</td>
<td>0.290</td>
</tr>
<tr>
<td>Coefficient of rolling</td>
<td>Not given</td>
<td>0.0075</td>
</tr>
<tr>
<td>resistance (Crr)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transmission type</td>
<td>CVT</td>
<td>5-speed</td>
</tr>
<tr>
<td>Final drive ratio</td>
<td>3.93</td>
<td>3.77</td>
</tr>
<tr>
<td>Engine peak power (kW)</td>
<td>43</td>
<td>43</td>
</tr>
<tr>
<td>Motor power (kW)</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Battery (kW)</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td>Total peak power (kW)</td>
<td>64</td>
<td>64</td>
</tr>
<tr>
<td>Peak power / test mass (W/kg)</td>
<td>46.9</td>
<td>45.6</td>
</tr>
</tbody>
</table>

*aGear ratios for simulations are as follows: Case 1, CVT = continuously variable transmission; Case 4, from low to high gear 2.91/1.64/1.07/0.75 (4-speed automat.); Cases 2, 3, & 5, 3.57/2.01/1.33/1.00/0.75 (5-speed man’1).

bN/A = Not applicable.

cAt 100% SOC.

We have worked with NREL on the conventional vehicle part of ADVISOR and on its calibration. To obtain performance-comparable comparisons of conventional vs. hybrid vehicles, it is necessary to model conventional vehicles as well as the hybrid. We chose the Saturn engine as a candidate contemporary U.S. manufactured engine, in part because detailed engine maps were available. In the end, we decided to focus on an engine pair with the same displacement and built on the same assembly line, the Saturn 1.9-L pair: a single overhead camshaft, two-valve (SOHC 2V) engine and a double overhead camshaft, four-valve (DOHC 4V) engine. The displacement of this engine pair typifies the smaller-displacement automotive engines manufactured in the United States for compact economy cars.

One possible effect of hybridization previously discussed relative to the Prius is the avoidance of high rpm operation. If the hybrid’s engine is similar in size (displacement) to that of the competing conventional vehicle, then the former will not be required to operate as often (if at all) at higher rpm values. The Prius’s engine, designed to operate at a maximum of 4000 rpm, takes advantage of this property. The SOHC 2V Saturn engine actually has higher efficiency than the DOHC 4V version at low rpm and low torque values, while the DOHC 4V has a much broader area of high-efficiency operation, extending to far higher rpm values. Lower average rpm would allow efficient operation at a lower power level, longer engine-on time, and fewer start-stop cycles, which should be good for engine life and for emissions. A SOHC 2V engine would also be cheaper. Honda’s most efficient four-valve engine is designed to operate as a three-valve engine below 2500 rpm, and other examples can be found where valves are kept closed for greater efficiency at low load. Thus, it is plausible that a 2V engine could be more efficient than a 4V of the same displacement.
in a given hybrid. With the assumption that neither candidate engine would operate above 4000 rpm (like the Prius), the extent of available torque/rpm combinations with less than 80 or 60 μG/sec-W of brake-specific fuel consumption appeared to be about the same, with the SOHC values “better positioned.” The SOHC 2V engine also obtains the highest fuel economy (but not necessarily the highest “performance-comparable” fuel economy) of the Saturn cars. For the hybrid, assuming that peak engine power is derated by setting a lower maximum rpm, the advantages of a DOHC 4V over a SOHC 2V for a given displacement are “chopped off.”

Using the ADVISOR model, we compare the fuel economy and emissions of a hypothetical conventional-drivetrain-equipped vehicle with a SOHC 2V Saturn engine to those for a pseudo-Prius with an Atkinson-cycle engine (Table 3). We fix several design values for the pseudo-Prius hybrid and the two “Prius-like” conventional vehicles. All three have the same frontal area, rolling resistance, and mass as the real Prius. (We construct two transmission cases for the conventional vehicle, a conventional five-speed manual transmission and an automatic transmission.) We have approximated performance comparability.

The pseudo-Prius simulation uses downsizing of an approximated Atkinson-cycle engine by reduction of the torque curve (i.e., displacement) rather than by reduction of peak rpm, so it does not match the Prius Atkinson-cycle engine in this respect. It does have higher peak efficiency than the Saturn engine, like the real Prius engine. In practice, we would expect that the conventional vehicle would have lower mass than the hybrid. We used the base Saturn SOHC 2V engine in the so-called Prius-like conventional vehicle with a five-speed manual transmission (“PriSat 5-speed”). The power-to-mass ratio of the resulting simulated vehicle was so similar to the Prius that the engine was not scaled. We used ADVISOR to estimate the change in fuel economy and performance that resulted from switching to an automatic transmission; this is the “PriSatAT” case.

Since the Prius has a higher profile than a Corolla or a Saturn (more frontal area), a lower coefficient of drag, lower rolling resistance tires, and greater mass, we constructed a case with a conventional Saturn-like vehicle, with one exception; we downsized the engine to obtain a 0-to-60 time equivalent to that estimated for the Prius at 100% SOC. This is the “Sat13 5-speed” case.

Thus, we consider five cases (see Table 4):

1. EPA Prius test results;
2. The ADVISOR “Prius-like” hybrid-drivetrain-equipped vehicle with pseudo-Atkinson-cycle engine and five-speed manual transmission (“Prius” Advisor);
3. The conventional-drivetrain-equipped, but otherwise “Prius-like,” vehicle with a conventional engine and five-speed manual, with comparable performance to that of the case 2 hybrid-drivetrain-equipped “Prius-like” vehicle at 100% SOC (PriSat5-speed);
4. Case 3, but with a four-speed automatic in place of the five-speed, with performance diminished (PriSatAT); and
5. A simulated Saturn with a smaller engine and five-speed transmission designed to just match the case 2 hybrid-drivetrain-equipped “Prius-like” vehicle in acceleration at 100% SOC (Sat13 5-speed).

The vehicle in case 5 has a smaller frontal area than do the “Prius-like” vehicles. Comparing cases
5 and 2 is like comparing the Toyota Corolla and the Prius with respect to frontal area. Does the frontal area of a hybrid need to be larger than that for a conventional vehicle? There should be advantages to a higher roofline and higher seating position for hybrids, some of which are designed to hold battery packs under passenger compartments. If hybrids come to be driven for a much higher proportion of VMT within urban areas, then a future CAFE for hybrids that allowed for this split (say, 75% urban and 25% highway) would avoid the disincentive for high frontal area associated with the present 55/45 CAFE split. The highway portion of the cycle is much more dependent on aerodynamic drag effects than is the urban portion, so the present CAFE regulations might unduly discourage a cost-effective high profile for hybrids.

Table 4 Performance and Fuel Economy Results for Four Simulated Vehicles and EPA Tested Vehicle

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Battery SOC</th>
<th>Case 1a</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
<th>Case 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-60mph</td>
<td>EPA Prius</td>
<td>0.00</td>
<td>13.9</td>
<td>14.1</td>
<td>20.7</td>
<td>22.5</td>
</tr>
<tr>
<td>full</td>
<td>(Atkinson)</td>
<td>0%</td>
<td>8%</td>
<td>4%</td>
<td>59%</td>
<td>73%</td>
</tr>
<tr>
<td>acceleration</td>
<td>Prius 5-spd</td>
<td>1.05</td>
<td>3.0</td>
<td>4.9</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>depleted</td>
<td>(Atkinson)</td>
<td>0%</td>
<td>8%</td>
<td>4%</td>
<td>59%</td>
<td>73%</td>
</tr>
<tr>
<td>0.02</td>
<td>Saturn SOHC</td>
<td>0%</td>
<td>8%</td>
<td>4%</td>
<td>59%</td>
<td>73%</td>
</tr>
</tbody>
</table>

Max. grade, 55 mph, 20 min

<table>
<thead>
<tr>
<th>Driving Cycle</th>
<th>Fuel Cycle</th>
<th>Cases</th>
<th>Fuel Cases</th>
<th>Fuel Cases</th>
<th>Fuel Cases</th>
<th>Fuel Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle (mph)</td>
<td>fuel (mpg)</td>
<td>2 vs. 1</td>
<td>(soc ch.)</td>
<td>2 vs. 3</td>
<td>(soc ch.)</td>
<td>2 vs. 4</td>
</tr>
<tr>
<td>NYCC</td>
<td>7.1</td>
<td>31</td>
<td>-12%</td>
<td>27.3</td>
<td>15.9</td>
<td>96%</td>
</tr>
<tr>
<td>Japan10/15</td>
<td>15</td>
<td>N/A</td>
<td></td>
<td>51.4</td>
<td>28</td>
<td>93%</td>
</tr>
<tr>
<td>FTP Bag 2</td>
<td>16</td>
<td>57d</td>
<td>-14%</td>
<td>48.8</td>
<td>31.3</td>
<td>68%</td>
</tr>
<tr>
<td>Full FTP</td>
<td>21</td>
<td>49</td>
<td>-3%</td>
<td>47.4</td>
<td>32.4</td>
<td>57%</td>
</tr>
<tr>
<td>SC03</td>
<td>21</td>
<td>34e</td>
<td>55%e</td>
<td>52.6</td>
<td>33.2</td>
<td>71%</td>
</tr>
<tr>
<td>FTP Bag 1c</td>
<td>26</td>
<td>38d</td>
<td>10%</td>
<td>41.7</td>
<td>31</td>
<td>44%</td>
</tr>
<tr>
<td>FTP Bag 3c</td>
<td>26</td>
<td>47d</td>
<td>13%</td>
<td>53.0</td>
<td>35.2</td>
<td>61%</td>
</tr>
</tbody>
</table>

| CAFE          | 33         | 45-51a | 2-6%a      | 52.3       | 37.2       | 46%       | 35.9       | 32%       | 39.8       |
| US06          | 48         | 37     | 14%        | 42.3       | 31.2       | 52%       | 27.9a      | 29%       | 32.8       |
| HFET          | 48         | 50-54f | 11-20f     | 60.0       | 45.3       | 29%       | 46.5       | 27%       | 47.1       |
| REP05         | 52         | N/A    | 33%        | 47.6       | 35.9       | 46%       | 32.5a      | 37.2       |

b These results are not simulations. Car and Driver (Bedard 1999) test results are inserted here.
c All cycles except FTP Bag 1 are either hot-stabilized or hot-started. FTP (bag1) is cold-started, Bag 3 is warm-started.
d These values are based on statistical fits of the type used by Heltman, Peralta, and Piotrowski, but not in the report. They are derived by us, using report data. Full FTP (FUDS) mpg built from these may not match the report estimate used here.
e Regarded by Heltman, Peralta, and Piotrowski (1998) as the least reliable of tests conducted. Fewest repetitions.
f Higher HFET value and resulting higher CAFE based on nonstandard test with 10 consecutive HFET tests.
g Did not meet trace (i.e., power was insufficient in a few seconds of the driving cycle to allow vehicle to match requested speed).

The five cases examined here may be “performance-comparable,” but they are far from “performance-equivalent.” Both Car and Driver (Bedard 1999) and the EPA (HPP) tested the Prius’s acceleration after attempting to completely deplete the battery, as well as at a normal
(unspecified) high state of charge. In both cases, the exact SOC for the test runs is unknown. Our simulation has three SOC levels: 100%, 20%, and 2%. We assume that the hybrids being studied are not intended to operate below 20% SOC. According to our simulation results, the vehicle’s acceleration capability should drop relatively slowly as SOC falls from 100% to 20%, but sharply as it falls below 20%.

Gradeability, an important design goal for the PNGV 3X vehicle, can be estimated with ADVISOR. The estimate for our “Prius” vehicle is that it can sustain 55 mph on a grade as steep as 4.7%; the PNGV goal is 6.5%. The three conventional vehicle configurations we simulated all exceeded the PNGV gradeability requirement; the automatic had the worst results, at 8.2%, while both manual transmission cases came in above 10%.

With regard to “performance-comparable” fuel economy, HPP estimated that “if one accounts for the performance difference between the Toyota Prius and the average 3000 lb car and the average subcompact car, the fuel economy advantage of the Toyota Prius is reduced to a 45 percent increase.” This comparison, which is implicitly for the CAFE-rated fuel economy, is apparently based on an average car, without specifying automatic or manual transmission. HPP assumed acceleration rates of 14.2 and 10.2-10.5 seconds, respectively, for the Prius and for competing gasoline vehicles (before mpg adjustment).

Comparing our simulated Prius-like hybrid (Prius Advisor) to the Saturn with a manual transmission and an engine downsized to have the same acceleration capability as the Prius Advisor simulation at 100% SOC (13.0 seconds) (Sat13 5-speed), we obtain a gain of 32%. An automatic transmission has not been accounted for, but we estimate it would put the fuel economy gain in the high 30s. Using the SC03 cycle in place of the FTP cycle and the US06 in place of the HFET cycle in the CAFE mpg calculations, we would obtain an estimated gain of 37% by Prius-like hybridization in comparison to a conventional vehicle (both with manual transmission).

Using the Gas Mileage Guide to “back out” the CAFE ratings of the 1.8-L 1998 U.S. Corolla, we obtain 35, 37, and 40 mpg, respectively, for the 3-speed automatic, 4-speed automatic, and 5-speed manual versions. Comparing these values with the potential EPA test CAFE combined ratings for the Prius, at 49(51) mpg we obtain an increase of 40% (46%) against the 3-speed automatic, 32% (38%) against the 4-speed automatic, and 23% (28%) against the 5-speed manual transmission. In Daniel Herauld’s acceleration tests of the 1999 Corolla, the 4-speed automatic and 5-speed manual obtain 0-60 times of 10.7 and 9.2 seconds, respectively. Thus, to make the Toyota Corolla “performance-comparable” to the Prius, one must downsize the engine or change gear ratios, either of which normally increases fuel economy. We can also make the comparison with the smaller Toyota Tercel, rated by EPA as a subcompact (as is the Prius). The Tercel has a 1.5-L engine, like the Prius, and gets only slightly better fuel economy than the Corolla. With the Tercel, the fuel economy gain numbers drop to 36% (41)% for the 3-speed automatic, 28% (33%) for the 4-speed automatic, and 36%(41%) for the 5-speed manual. This “same manufacturer” comparison puts the high-end estimate of mpg gain from “Prius-ization” in a competing vehicle package at 46% and the low end at 22%.

If we examine the effect of the hybrid drivetrain (and Atkinson-cycle engine) in a vehicle with otherwise equivalent transmission type, mass, rolling resistance, frontal area, and coefficient of drag (but a SOHC 2V engine in the conventional drivetrain), we estimate that hybridization on the CAFE cycle obtains a 41% increase in mpg (Prius Advisor vs. PriSat5-speed). The conventional
drivetrain allows repetition of the best acceleration times of the hybrid, as well as climbing a grade with more than twice the slope. Making this same comparison, but with the automatic transmission results, we see a 46% improvement in CAFE mpg (Prius Advisor vs. PriSatAT). (Can mass can be held constant in a real conversion from conventional to hybrid drivetrain? It may be possible if motors and batteries increase moderately in power density compared to the values used for the Prius, but it is unlikely with present Prius components.)

Toyota compared the Prius to an automatic-transmission-equipped Corolla, so we can compare the Japan 10/15 cycle model results for the Prius Advisor case with the PriSatAT simulation. The result is an estimated 93% gain in mpg. This is less than Toyota obtained in its comparison, but the percentage difference is similarly large and much greater than the CAFE results. Comparing the Prius Advisor case to the PriSatAT simulation for the NYCC cycle, we estimate a 96% gain in mpg. Clearly, ADVISOR predicts very high percentage gains in mpg in congested urban driving conditions through hybridization. Moreover, the gap between hybrid and conventional vehicle mpg increases sharply in favor of the hybrid as congestion and/or the number of stops per mile increases.

Consumers are likely to recognize this attribute of hybrids and to use them so as to take advantage of their high fuel economy in congested or stop-and-go driving. Suppose that consumers select and use hybrids in this way, such that the urban VMT of hybrids is 75%. Assuming the SC03 cycle is more representative of urban driving and the US06 cycle more representative of highway and interurban driving, we estimate (by a formula like the CAFE formula) that the fuel economy gain from replacing a Sat13 5-speed with a Prius Advisor vehicle for this type of use would increase from 32% to 40% (a 25% increase).

"Errors" in Estimates. The term "error" is used loosely here. Developing and refining the ADVISOR model is a continuous, repetitive process of generating results, evaluating, and revising. It is necessary to distinguish between instances where the model’s programming should be changed and those where disparate outcomes can be accounted for by different input assumptions or component characteristics. Differences between ADVISOR estimates for case 1 (EPA tests of the Prius) and case 2 ("Prius" Advisor) vary from absolute values of 55% (SC03) to 3% (FTP and CAFE combined). The first "correction" for the SC03 cycle would be to add an air-conditioner load model to ADVISOR; without this load, the ADVISOR SC03 results are simply an estimate of the effects of the SC03 speed time trace. [Also, SC03 is the least reliable EPA test, so the difference might narrow with further testing (HPP 1998).]

The next largest difference is 20%, and for the similar-speed Bag 1/3 and Bag 2 cycles, the absolute difference is 10-14%. The differences in the ADVISOR simulation relative to the EPA tests are all positive above 20 mph and negative below 20 mph, suggesting that ADVISOR might be overestimating Prius’s benefits at average speeds above 20 mph and underestimating them below this speed. This bias may arise because the real Prius has a CVT, while the simulated "Prius-like" hybrid has a 5-speed manual transmission. For example, the Honda Civic Coupe base engine ("DX" model) is available with a 5-speed manual and a 4-speed automatic. The Gas Mileage Guide city/highway ratings for the 5-speed are 32/37, and that for the automatic is 28/35; in switching to the conventional automatic, the percentage drop in city mpg is greater than that in highway mpg. For the "HX" version of this coupe, which has a CVT option instead of a conventional automatic, the 5-speed rating is 35/43 and the CVT rating is 34/38; in the CVT-for-manual switch, the percentage drop in highway mpg is considerably greater than for city mpg. The
CVT appears to be very good in “city” driving, but not on the highway. The Prius CVT is not the same technology as Honda’s, but the pattern discussed here is at least partly consistent with the patterns seen with our simulated “Prius” vs. the actual one. Data on the Prius CVT are not yet available to incorporate into ADVISOR.

**Other Recent Experiments.** Our results, yielding even lower “performance-comparable” fuel economy gains than those reported by the EPA, may seem unsupportive of hybrid vehicles. However, the study of modern hybrid vehicles is still young; surprises may yet be in store. In examining the effects of hybridization on vehicles designed to accelerate to 60 mph in eight and ten seconds, we have found that the percentage gains associated with hybridization rise sharply as the 0-60 performance capability of the vehicles (both hybrid and conventional) are increased (holding the gradeability requirement of the hybrid version constant). The calculations used to produce Figure 2 were based on the same engine for the hybrid and conventional vehicles (i.e., no Atkinson-cycle engine in the hybrid), so the fuel economy gain for the parallel vehicle dropped to about 20% vs. the estimated 32% here. This implies that the Atkinson-cycle engine accounts for a part of the 32% estimated gain in Prius mpg (about a third), which is very similar to the 40% share of the gain that Hermance (1998) indicated was estimated (on a different driving cycle) by Toyota. More important, the estimates indicate that the CAFE-rated gain in fuel economy from hybridization for a higher-performance vehicle (eight-second 0-60 time) could reach 70%. Many six- and eight-cylinder light-duty vehicles sold in the United States have acceleration capability close to this level. Unfortunately, providing a high 0-60 acceleration capability in hybrids by use of larger electric motors and battery packs is more expensive than doing so by enlarging the engine in a conventional vehicle. Toyota has announced that the engine for the U.S. version of the Prius will not be limited to a 4000-rpm maximum (Buchholz 1998). This change, which should be relatively easy to make, would alter the “performance-comparable” comparisons. Effects on fuel economy would probably be minimal, although other modifications to improve fuel economy may be discovered.

**CONCLUSIONS**

The benefits or disbenefits of grid-independent gasoline-fueled hybrid vehicles (such as the Toyota Prius) vs. well-controlled conventional gasoline vehicles with respect to criteria pollutants remain uncertain. It appears that both conventional and hybrid vehicles can be designed for very low emissions, with neither having an inherent advantage. When a vehicle is extremely clean with respect to criteria pollutant emissions, emissions from the fuel cycle begin to dominate; fuel economy becomes as important in full fuel cycle emissions reduction as in vehicle tailpipe emissions reduction. At this point, attention shifts from the vehicle’s criteria pollutant tailpipe emissions to its fuel economy and CO₂ emissions. Significant fuel consumption and greenhouse gas emissions reductions are clearly possible with grid-independent hybrid vehicles if they are used to best advantage.

Hybrid vehicles have real potential to reduce fuel use, but overselling the advantages of present-technology hybrids might create a skeptical backlash against this technology. Consumers need to be educated fully and fairly about these vehicles, including the conditions under which their use is likely to make sense.

The best fuel economy increases with hybrids will be obtained in congested urban areas, or (in multi-vehicle households) as vehicles used primarily for urban travel under congested conditions.
To understand the fuel economy benefits that a hybrid vehicle is likely to realize in use, one has to understand the driving cycle(s) used to test the vehicle in relation to likely real-world driving patterns. The pattern of use of hybrid vehicles a decade from now is likely to be far different than it was for 1970s gasoline vehicles (when CAFE regulations were established), and such vehicles should be evaluated on their own merits as it becomes clear how they will be used. Rather than require that these vehicles fit the regulatory mold set up over decades for the conventional gasoline vehicle, we suggest a period of regulatory flexibility (combined with accountability) for those manufacturers willing to seek the proper market niches for these vehicles. The new EPA VMEP program offers a model for such regulatory flexibility.

Continued use and refinement of computer simulations and evaluation of possible hybrid vehicle configurations could lead to more effective development of regulations and test procedures particularly suitable to hybrid vehicles, as well as more cost-effective use of these vehicles by consumers. The most desirable configurations of U.S. hybrids remain to be discovered. Questions include whether hybrids should be grid-connectable or grid-independent, whether they should use a parallel or series configuration, and whether they should be designed for high performance or simply for acceptable performance.

REFERENCES


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Fig. 1 Change in voltage (power) as a function of state of charge for a simulated NiMH battery pack for the Prius Advisor simulations.

Fig. 2. A preliminary estimate of the gains in fuel economy through hybridization, as a function of performance level and type of hybrid.