ANL/ESD/02-2

# Hybrid Electric Vehicle Technology Assessment: Methodology, Analytical Issues, and Interim Results

ARGONNE NATIONAL LABORATORY
TRANSPORTATION
TECHNOLOGY R&D CENTER

**Center for Transportation Research**
**Argonne National Laboratory**

Operated by The University of Chicago,
under Contract W-31-109-Eng-38, for the

**United States Department of Energy**

Argonne National Laboratory, with facilities in the states of Illinois and Idaho, is owned by the United States Government and operated by The University of Chicago under the provisions of a contract with the U.S. Department of Energy.



Available electronically at http://www.doe.gov/bridge

Available for a processing fee to U.S. Department of Energy and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: (865) 576-8401
fax: (865) 576-5728
email: reports@adonis.osti.gov

ANL/ESD/02-2

# Hybrid Electric Vehicle Technology Assessment: Methodology, Analytical Issues, and Interim Results

by S. Plotkin, D. Santini, A. Vyas, J. Anderson, M. Wang, J. He,* and D. Bharathan*

Center for Transportation Research, Energy Systems Division,
Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois 60439

October 2001

Work sponsored by the United States Department of Energy,
Assistant Secretary for Energy Efficiency and Renewable Energy,
Office of Transportation Technologies

* J. He is currently affiliated with Lucent Technologies, Naperville, Illinois. D. Bharathan is currently affiliated with the National Renewable Energy Laboratory, Golden, Colorado.

## NOTICE

This technical report is a product of Argonne's Energy Systems Division. For information on the division's scientific and engineering activities, contact:

Director, Energy Systems Division
Argonne National Laboratory
Argonne, Illinois 60439-4815
Telephone (630) 252-3724

Publishing support services were provided by Argonne's Information and Publishing Division (for more information, see IPD's home page: http://www.ipd.anl.gov).

This report is printed on recycled paper.

ANL/ESD/02-1 HYBRID ELECTRIC VEHICLE TECHNOLOGY ASSESSMENT: METHODOLOGY, ANALYTICAL ISSUES, AND INTERIM RESULTS

# Contents

## Figures

## Tables

# Acknowledgments

Funding for this study was provided predominantly by Dr. Philip Patterson, manager of Planning and Analysis for Tom Gross, Deputy Assistant Secretary of the Department of Energy's Office of Transportation Technologies. Some funding was also provided by Paul McArdle, then of the Office of Technology Utilization within the Office of Transportation Technologies, whose director is David Rodgers.

The authors would like to acknowledge the strong support and valuable advice of Dr. Philip Patterson of the Office of Transportation Technologies, U.S. Department of Energy. Keith Wipke and Mathew Cuddy of the National Renewable Energy Laboratory, the designers of the ADVISOR model, were extremely generous with their time and advice and were invaluable to this study. Authors appreciate the time and effort put in by the reviewers: Dr. Andrew Burke of University of California at Davis; David Bauner of MTC AB, Sweden; Dr. Ata Khan of Carlton University, Ottawa, Canada; Rogelio Sullivan of the Office of Advanced Automotive Technologies, U.S. Department of Energy; and Dr. Feng An of Argonne's Center for Transportation Research. Their constructive comments were very helpful. Thanks are also due to our technical editor, Madonna Pence, and Argonne's Information and Publishing Division personnel for preparing the manuscript and graphics. Although several persons helped make this report possible, the authors are solely responsible for its contents.

# Notation

| | |
|---|---|
| 4WD | four-wheel drive |
| ac | alternating current |
| ADVISOR | Advanced Vehicle Simulator |
| ANL | Argonne National Laboratory |
| APU | auxiliary power unit |
| AWD | all-wheel drive |
| AWMA | Air and Waste Management Association |
| BMEP | brake mean effective pressure |
| CAFE | corporate average fuel economy |
| CARB | California Air Resources Board |
| $C_d$ | coefficient of drag |
| $CH_4$ | methane |
| CO | carbon monoxide |
| $CO_2$ | carbon dioxide |
| $C_r$ | coefficient of rolling resistance |
| CV | conventional vehicle |
| CVT | continuously variable transmission |
| dc | direct current |
| DI | direct injection |
| DISC | direct injection stratified charge |
| DOE | U.S. Department of Energy |
| EIA | Energy Information Administration |
| EPA | U.S. Environmental Protection Agency |
| EV | electric vehicle |
| FHEV | full hybrid vehicle |
| FTP | federal test procedure |
| FTPRP | Federal Test Procedure Revision Project |
| FUDS | federal urban driving schedule |
| HC | hydrocarbon |
| HEV | hybrid electric vehicle |
| HEVCOST | Hybrid Electric Vehicle Component Sizing and Vehicle Cost (model) |
| HEVGrid | grid-connected hybrid |
| HEVTA | Hybrid Electric Vehicle Technology Assessment |
| HVAC | heating, ventilation, and air-conditioning |
| ICE | internal combustion engine |
| JPL | Jet Propulsion Laboratory |
| kg | kilogram |
| L | liter |
| LDV | light-duty vehicle |
| MHEV | mild hybrid vehicle |

| | |
|---|---|
| mph | miles per hour |
| $N_2O$ | nitrous oxide |
| NCHRP | National Cooperative Highway Research Project |
| NiMH | nickel metal hydride |
| $NO_X$ | nitrogen oxides |
| NREL | National Renewable Energy Laboratory |
| NVH | noise, vibration, and harshness |
| NYCC | New York City driving cycle |
| OBPU | onboard power unit |
| OEM | original equipment manufacturer |
| OTA | Office of Technology Assessment |
| OTT | Office of Transportation Technologies |
| PNGV | Partnership for a New Generation of Vehicles |
| PU | power unit |
| R | range |
| REP05 | Representative No. 5 driving cycle |
| RFG | reformulated gasoline |
| SI | spark ignition |
| $SO_2$ | sulfur dioxide |
| SOC | state of charge |
| SOHC | single overhead cam |
| TA | technology assessment |
| TDI | turbocharged direct injection |
| ULEV | ultra-low emission vehicle |
| ULS | ultralightweight steel |
| US06 | U.S. No. 6 driving cycle |
| VOC | volatile organic compound |
| VVC | variable valve control |
| W | watt |
| W/h | watt per hour |
| Z60 | 0-60 mph acceleration |
| ZEV | zero emission vehicle |

# Summary

## Introduction

This report presents the interim results of the Argonne National Laboratory (ANL) Hybrid Electric Vehicle Technology Assessment (HEVTA). Hybrid electric vehicles, or HEVs, are vehicles with drivetrains that combine an electric drive (including electric motor and some form of electricity storage) with a refuelable power plant (e.g., an internal combustion engine). This combination is capable of significantly improving vehicle efficiency (see Box 1). Toyota's Prius and Honda's Insight cars are both HEVs, the first commercial examples.

A full technology assessment (TA) examines the effects on society of introducing a new technology or expanding the use of an existing technology, including a full range of costs and benefits. This assessment focuses particularly on the energy impacts and costs of HEVs. The focus is on the individual vehicle. We do not attempt to project the impacts of alternative scenarios when large numbers of HEVs gradually penetrate the vehicle fleet.

**Box 1. How a Hybrid Drivetrain Saves Energy**

The primary goal of using a hybrid drivetrain is saving energy. By using an electric motor and battery to augment a vehicle's engine, energy can be saved by several means:

- **Regenerative braking.** The motor is used in generator mode to brake the vehicle, generating electricity to be stored in the battery and thus recapturing some of the energy normally lost as heat in conventional brakes.
- **Engine downsizing.** The power added by the electric drive may allow the engine to be downsized, maintaining most engine operation at a higher percentage of rated torque, which is generally more efficient.
- **"Idle-off."** Use of the motor as a starting motor, with the battery available to run the accessories, allows the engine to be turned off during stops (and perhaps also during braking and coasting), saving energy that would otherwise be lost during these events.
- **Electric launch.** In some configurations, the motor alone can be used to accelerate from a stop, avoiding a driving mode where the engine in a conventional drivetrain would be particularly inefficient.

The HEVTA uses two primary models:

1. ADVISOR (Advanced Vehicle Simulator), built by the National Renewable Energy Laboratory, estimates the second-by-second energy use and emissions of a vehicle over a defined driving cycle. Later versions of ADVISOR also allow the power capacity of the drivetrain components to be defined from a set of performance requirements, e.g., 0-60 mph acceleration (Z60) times. ANL has also built a performance model that sizes the drivetrain based on performance requirements; this model is embedded in HEVCOST (Hybrid Electric Vehicle Component Sizing and Vehicle Cost model).

2. HEVCOST first sizes the components of the vehicle, then estimates its retail price by individually pricing the drivetrain components in an HEV that are not shared with a similarly performing conventional vehicle (CV), e.g., battery, engine, and other drivetrain components, using equations based on their power and energy requirements, and adding these prices to a pre-established price for the common components. In other words, the model assumes that hybrids and CVs are essentially identical except for some minor structural additions to the hybrid to accommodate the electric drive, plus the drivetrain itself.

## Description of the Vehicles Evaluated

The vehicles are midsized passenger cars, with the interior space of such cars as the Chrysler Intrepid and Ford Taurus and the external dimensions of the slightly smaller Chrysler Cirrus and Chevrolet Malibu. The current versions of the Intrepid and Taurus weigh about 1,418 kg (3,125 lb); the 2010 CV versions will weigh about 1,225 kg (2,767 lb). The “gliders” (bodies without drivetrains) are projected to weigh about 922 kg (2,029 lb) in 2010. The HEV versions will have gliders that are 5% heavier to account for structural reinforcement needed to accommodate heavier drivetrain components.

The CVs and HEVs share all nondrivetrain components,[1] including basic body structure, tires, and aerodynamic shape. Four types of hybrid design are examined:

1. **Parallel grid-independent full hybrid (FHEV),** with engine sized to maintain a specified constant gradeability and battery/motor sized to satisfy (in concert with the engine) the Z60 requirement. Grid independence means that all energy requirements are satisfied by fuel carried onboard; batteries are recharged by electricity from engine-driven generation and regenerative braking.

2. **Parallel grid-independent mild hybrid (MHEV),** with engine power midway between full hybrid and CV and battery and motor sized to satisfy the Z60 requirement.

3. **Series grid-independent FHEV,** with engine and electric motor (continuous rating) sized for gradeability, battery sized to provide boost for acceleration requirements, and electric motor (maximum power) sized for full acceleration power requirements.[2]

4. **Parallel and series grid-dependent hybrids,** designed to operate part of the time as full electric vehicles, so battery and electric motor are sized to satisfy a separate electric vehicle (EV) acceleration requirement, and the engine is sized to provide the minimum specified gradeability.

---

[1] Except for the small weight gain of the HEV body.

[2] In other words, there are two separate sizing criteria for the electric motor. Although the gradeability criterion requires less power than the acceleration criterion, the motor’s continuous power rating will be lower than its peak rating. Therefore, actual motor size may be determined by either the acceleration or the gradeability criterion, depending on motor design and the gradeability and acceleration criteria used.

The HEVs examined use simple control strategies. Parallel vehicles use the motor to launch the vehicle and provide all torque below a specified launch speed, with the engine turned off. Above that speed, the engine is turned on and used as a load follower, generally satisfying all torque requirements up to the engine's maximum capability. The exception occurs if torque demanded falls below a set limit. For example, during a downhill coast or during braking, the engine shuts off. When the engine is turned on, the motor assists the engine only if the desired torque is higher than the engine's maximum capability (e.g., during high acceleration). During braking, the motor provides all braking force up to its maximum capacity, feeding the electricity generated to the batteries; the mechanical brakes provide any additional braking force needed. Finally, if the battery state of charge (SOC) goes below a specified lower bound, the engine is designed to increase its torque output above the level demanded by the tractional load and accessory power load, with the excess torque passing through the motor (acting as a generator) to charge the battery.

## Results

If compared to recent widely publicized studies that evaluate hybrid vehicle technology, this one is unique with respect to the variability in types of hybrids, potential levels of performance, and variety of driving cycles evaluated. It is narrow in the sense that it emphasizes cost only, ignoring issues of emissions of criteria pollutants and the rich variability of consumer preferences. Thus, it evaluates only the critical aspect of the potential marketability of hybrids. The results are encouraging enough to recommend that examinations of their value for purposes in addition to saving fuel for the owner are important, and could make a significant difference to market success. For example, there might be a change of consumer valuation of a capability for all-electric operation in an emergency, in light of the terrorism of September 11. Thus, this study has some strengths and weaknesses that readers should be aware of. Wider reading on the attributes of hybrids is recommended, but this study does complement others available.

With regard to the focus of this study – costs – the findings imply that research to reduce dollar cost per unit of performance of electric drive components remains highly desirable. Thus, the aggressive research goals of DOE – which if successful would drop costs to a level where hybrids would be attractive on a net cost basis only – remain important. In our analysis, we do not see such costs naturally emerging from market forces. Without any cost reduction breakthroughs, we estimate that parallel "mild" hybrids should be within striking distance of widespread marketability after several years of experience in producing the vehicles, and after production and sales reach hundreds of thousands of vehicles. It is easy to imagine "niche market" success of such hybrids based on factors other than cost that are important to consumers and society. However, it is difficult to imagine widespread displacement of the conventional vehicle at the costs that we estimate, unless (as we discuss in the report) fuel prices rise considerably from levels of the last decade, and remain high. The latter alternative is less desirable than achievement of cost-for-performance breakthroughs through continuing research and development of drivetrain components. Specifics on our results follow.

The ADVISOR model was used to evaluate the vehicles' performance over seven driving cycles, ranging from the stop-and-go NYCC (New York City Cycle) to the fast and high-power

REP05 (Representative No. 5 Cycle), with year 2010 vehicle characteristics. The HEVCOST model evaluated vehicle costs for years 2005-2020. Key results are as follows:

1. **HEVs achieve the largest percentage gain in fuel economy over CVs on the slowest driving cycles**. This is not a surprising result, since the inefficiencies of slow, stop-and-go driving – high idling losses, high braking losses, highly inefficient engine operation – are exactly the losses hybrid drivetrains are designed to combat. The implication of this conclusion appears to be that HEVs will be most advantageous in dense urban environments. This conclusion must be tempered, however, by the possibility that miles driven per vehicle will be lower in areas where traffic is slower; if so (and available data imply that it *is* so), gallons of gasoline saved per vehicle per year, the most relevant measure of benefit, will not vary as much across different driving environments as implied by the percentage gain results.

2. **Parallel HEVs are likely to be more efficient than series HEVs, with both having fuel economy that is less sensitive to performance than a CV.** The clearest difference between the two types of hybrid is that the parallel HEV's engine drives the wheels directly through the differential and transmission for much of its operation, whereas the series HEV's engine must first generate electricity through the generator and then drive the wheels through the motor. The latter is a less efficient route, given existing electric drive component efficiencies. This could change, of course. The lack of sensitivity of HEV fuel economy to required performance may be largely an artifact of the design rule used in this study for FHEVs; a faster Z60 time is obtained by increasing the power capacity of the electric motor and battery rather than that of the engine, whereas vehicle efficiency is quite dependent on engine rated power relative to average load. Generally, the higher the ratio of rated power to average power, the less efficiently the engine operates during normal driving.

3. **Hybrids' mpg improvement over CVs increases as the acceleration times go down.** The obvious result of HEV fuel economy insensitivity to Z60 time is that moving toward faster vehicles will tend to increase the efficiency advantage of the hybrid drivetrain, since CV fuel economy is very sensitive to engine power requirements. However, it is important to stress that the "faster" HEV will retain its limited gradeability and towing capability, while the faster CV will increase its previous advantage over the HEV in these performance factors.

4. **Parallel hybrids are cheaper than series.** The crucial cost difference between series and parallel hybrids is caused by the electric motor – the parallel HEV's motor provides boost power to supplement the engine, while the series HEV's motor must provide all needed tractive power and thus must be much more powerful (and more expensive). The parallel HEV requires a more expensive automotive (multigear) transmission because the engine drives the wheels, whereas a series HEV requires at most a two-gear transmission (and possibly just one), because the motor, which solely drives the wheels in this configuration, can provide high torque through a wide speed range. Nevertheless, the motor is a very expensive component, and its cost far outweighs the effect of the transmission difference.

5. **Demanding better acceleration performance is expensive.** The U.S. automobile market has been steadily moving toward lower and lower Z60 times. This is expensive in a CV, but is considerably more expensive – on the order of twice as expensive to move from a 12-second Z60 to an 8-second Z60 – for a parallel HEV, using this study's design rule (engine sized for gradeability, battery/motor for Z60). This observation led us to add "mild" hybrids (hybrids with more engine and less motor and battery) to the analysis, because we concluded that the trend to faster vehicles would drive designers of HEVs in this direction.

6. **HEV life cycle costs are extremely sensitive to assumptions, but they appear likely to exceed CV life cycle costs unless fuel prices rise to well over today's levels.** Electric drivetrain components are extremely expensive, but prices should be reduced over time with learning and higher production rates. Thus, breakeven fuel prices – prices for which CV and HEV life cycle costs would be even – will come down over time. However, our best guess at component prices yields very high breakeven gasoline prices for our hybrids – about $2.50/gallon for a year 2020 parallel hybrid with 8-second Z60, and considerably higher for lower performing vehicles and for earlier years. Prospects look better for mild hybrids (breakeven prices below $2.00/gallon by 2020 for an 8-second Z60 mild hybrid), but lower performing vehicles have breakeven prices well above $2.00/gallon. We note that these estimates are for the average U.S. driver. For those hybrid vehicle owners who spend more hours driving than the average, the breakeven point will be a bit lower.

7. **In comparison to CVs, grid-connected HEVs (HEVGrids) can achieve large reductions in oil use, and lesser but significant reductions in greenhouse emissions and total energy use, but at very high purchase and life cycle costs.** On the other hand, grid-connected HEVs do not cost a great deal more than grid-independent HEVs (if the latter must match their maximum acceleration performance with their engines on), yet they use substantially less oil and result in a moderate reduction in greenhouse emissions. Grid-connected HEVs are attractive conceptually because they are capable of operating part-time as EVs and can "refuel" a portion of their travel from the electric grid, which offers significant air quality benefits, as well as the potential to capture large savings in oil use, and can significantly reduce overall energy use and greenhouse emissions. Our estimates imply, for example, that a grid-connected HEV with 33-mile range might use one-third as much gasoline as a CV that matched its hybrid-mode acceleration performance (that is, with its engine on), and about half as much as a CV matching its all-electric acceleration performance. However, these benefits come at a high price, both in initial investment and in life cycle costs. Comparing the same vehicles, we estimate the CV to be from 20 to 24% cheaper than the comparable HEVGrid in 2020, with life cycle costs lower by 5 cents or more per mile in 2020.

8. **Long-run (i.e., 2020) incremental prices of the parallel HEVs examined in this study vary from a 12% increment to a 32% increment, increasing as one proceeds from a mild hybrid to a full hybrid to a grid-connected hybrid.** The estimates for parallel hybrids range from 12 to 14% for the three MHEV cases, from 16 to 19% for

the FHEV cases, and from 25 to 32% for the HEVGrids with all-electric range from 23 to 33 miles.

The percentage increase estimates in this study may be compared to those developed in the recent study by Weiss et al. (2001), done at MIT, and by Graham et al. (2001), under EPRI management. The one comparable case from the MIT study is an MHEV. The estimated increase in price is 9%, less than estimated in this study. The base method price increases from the EPRI study for the two FHEV cases examined are 20 and 21%. Though published earlier, the price estimates in the EPRI study were completed later than for this study. ANL's HEV cost estimation team worked with the EPRI study group to generate price increase estimates that reflect revised electric drive costs from those in this study. More optimism about component characteristics was included. The "ANL method" price increase estimates for the two EPRI FHEV cases were 12 and 13%, well below the 16 to 19% estimated here. The largest difference resulted from more optimism concerning battery costs. The EPRI base method price increase estimates for the hybrid with about 20 miles of all-electric range was 32% – at the top end of this study's estimate of 25 to 32%. The revised "ANL method" gave 21% for this EPRI case.

Compared to the one MHEV case in the MIT study, this study's MHEV price increase estimates are a bit higher. Compared to the two comparable FHEV and one comparable HEVGrid cases from the EPRI study, the estimates in this study are a bit lower. The revisions of the ANL method initiated in this study, and included in the EPRI study, are more optimistic than this study's estimates. A significant part of the difference arose from observation of rapid improvement of components used in marketed hybrids. This rapid improvement, occurring over less than two years, suggests that this study may be unduly pessimistic, at least about the rate of cost reduction that is possible for hybrid vehicle components.
The key hybrid components – battery (or other storage device), electric motor, and controller – are all under continuing development. DOE has established aggressive goals to reduce energy storage costs to levels well below those used in this study. Potential exists to substantially reduce motor and power electronics costs as well. Although the probability of achieving very high levels of cost reduction is not clear, success would significantly improve hybrids' cost-effectiveness and their prospects for mass market penetration.

## Methodology Issues

The tools and methods available to the study team have limitations that the reader should understand in order to judge the robustness of the results and to be guided in future analysis. Key issues are:

1. **Comparing CVs to HEVs.** A key goal of the study is to compute unambiguously the changes in energy use and emissions associated with introducing hybrid vehicles. The two HEVs introduced to the U.S. marketplace both have changes from current vehicles that go beyond substituting a hybrid drivetrain for a conventional one, e.g., the Insight

has a low-mass aluminum body, and the Prius has acceleration performance somewhat below typical vehicles of its class. The HEVTA attempts to avoid comparing apples to oranges by assuming that all physical aspects of a CV and HEV being compared, aside from those dictated by hybridization, are identical. In other words, we assume that both vehicles have identical bodies and identical tires except for a small weight gain by the hybrid to "beef up" its structure for electric drive components.[3] Furthermore, we assure the comparability of a measure of performance by designing the hybrid drivetrain to match the Z60 capability of the CV to which it is being compared. However, there are a number of problems with creating a perfect CV/HEV comparison, some of which are associated with limitations to the tools we have, and some of which are associated with inevitable differences between CVs and HEVs.

- **Gradeability.** Most hybrids will have limitations to their gradeability because of the combination of engine downsizing and sharp limits to battery capacity. If long-term gradeability is limited to what can be achieved by the engine operating alone (to avoid draining the battery), an HEV with Z60 capability equal to that of a CV will have substantially less grade-climbing capability (as well as towing capacity). Thus, an HEV/CV pair will rarely be performance-equivalent.

- **Establishing equivalent acceleration performance.** In our analysis, the Z60 of the vehicles is the crucial variable for achieving performance equivalence. However, there is no industry standard for measuring Z60, and our research shows that different test organizations have arrived at significantly different Z60 estimates for identical vehicles, apparently because of different test protocols. If anything, the sharp differences in CV and HEV operations make it more difficult to match Z60 performance. In other words, there is no unambiguous way to define a matched CV/HEV pair of equal Z60 performance.

- **Selecting a CV/HEV engine pair.** In comparing a paired CV and HEV, it is important to avoid attributing to hybridization any effects that are due to technology differences that are irrelevant to hybridization. In some cases, this is easy. For example, in comparisons between the Toyota Prius and Toyota Corolla, the Prius has variable valve control (VVC) and the Corolla does not. Because hybridization is not a prerequisite for VVC and does not even make its use more logical, its positive effect on fuel economy should not be counted as a hybridization benefit. In many cases, however, defining a paired set of CV/HEV power plants is not easy. It is difficult even when the conceptual decision is made to use two engines of identical technology but different power,[4] because it is unlikely that two such engines with fuel consumption and emissions maps of

[3] Admittedly, this is a simplistic assumption because it disregards variations in the amount of additional structural materials caused by differences in hybrid performance and potential electric range.

[4] Moreover, it is not clear that "identical technology" is in fact an appropriate goal for a CV/HEV engine pair, since the demands on the engine are quite different in CV and HEV drivetrains.

the appropriate size will be available. The more practical method of analyzing such an engine pair is to use mathematical scaling techniques to construct pairs of engine maps from the maps of a single engine. Unfortunately, such scaling may introduce significant errors into the maps.

2. **Engine maps.** Aside from the scaling problem discussed above, there are significant problems with obtaining adequate engine maps for HEV engines. First, there are few emissions maps available; in attempting to model vehicle emissions, we were forced to rely on maps constructed from second-by-second emissions data that stretched the measurement state-of-the-art. Second, available fuel consumption maps contain few data at idle and none at negative load (during braking and coasting) despite the substantial fuel consumed during these conditions on the standard driving cycles. We "filled in" the fuel consumption maps with data we obtained from government testing programs.

3. **Emissions modeling.** Emissions rates are extremely sensitive to engine and catalyst changes that are difficult to model accurately. For example, small variations in engine conditions can cause large changes in emissions, but available transmission models for multiple vehicle applications are unlikely to accurately represent where on the engine map the engine will operate as commanded by the transmission. In fact, the original transmission model in ADVISOR moved the engine into regions of the engine maps in which real-world engines would not operate. Also, tailpipe emissions are sensitive to temperature and other variations in the catalyst that are hard to predict and likely to vary with changes in drivetrain design strategy. In light of continuing skepticism about the emissions results, as well as real-world results for the Prius and Insight hybrids that contradict early (high) hybrid estimates from our early modeling work,[5] ANL has chosen to report only energy use results in this report.

4. **Accounting for costs and other design factors.** ANL's analysis of equivalent CVs and HEVs is based on a simple set of performance targets and design rules rather than on the sophisticated design process that would actually occur in developing a commercial vehicle. This basis will tend to distort some of the conclusions about the way energy use varies with changes in performance targets and other factors, since the simple design rules may cause changes in the vehicle configuration that are quite different from the way real-world designers might react to the same target changes.

5. **Accounting for technological change.** Because this analysis attempts to compare CVs and HEVs in the future (all the ADVISOR runs and the summary cost results presented in Section 4 are keyed to the year 2010), ideally the analysis would account for likely technological changes that would be expected to have occurred by that date. Although the analysis incorporates projections about change for some technologies, such as nickel metal hydride (NiMH) batteries, other technologies are left unchanged from

[5] Santini, D.J., J. Anderson, J. He, S. Plotkin, A. Vyas, and D. Bharathan, 1999, *Gasoline-Fueled Hybrid vs. Conventional Vehicle Emissions and Fuel Economy,* Ninety-Second Annual Meeting and Exhibition of the Air and Waste Management Association, Paper 99-851, St. Louis, Mo., June.

their 1990s versions. For example, the difficulty of changing engine fuel consumption maps to account for technological change has led ANL to leave the available maps unchanged; the maps used are from a 1995 Saturn. One effect of this particular decision may be to increase the apparent fuel economy boost of the HEV, because a more modern engine might reduce some of the inefficiencies that the HEV drivetrain is designed to target. On the other hand, we did not assume that hybridization might allow use of a more efficient engine. In fact, the Prius uses a more efficient Atkinson-cycle engine – one that could not be used in a conventional vehicle. In addition, the great uncertainty of the future rate of technological change could affect the accuracy of the boost estimate in either direction. For example, the assumed year 2010 energy density of the HEVs' NiMH batteries is actually substantially *below* the *actual* energy density of the recently introduced MY2000 Prius; technological progress has moved much faster than we assumed when we began this analysis.

# Section 1
# **Introduction**

This report presents the results of the first phase of Argonne National Laboratory's (ANL's) examination of the costs and energy impacts of light-duty hybrid electric vehicles (HEVs).[6] We call this research an HEV Technology Assessment, or HEVTA. HEVs are vehicles with drivetrains that combine electric drive components (electric motor, electricity storage) with a refuelable power plant (e.g., an internal combustion engine). The use of hybrid drivetrains is widely considered a key technology strategy in improving automotive fuel efficiency. Two hybrid vehicles – Toyota's Prius and Honda's Insight – have been introduced into the U.S. market, and all three auto industry participants in the Partnership for a New Generation of Vehicles (PNGV) have selected hybrid drivetrains for their prototype vehicles.

The HEVTA is being conducted for the U.S. Department of Energy (DOE), Office of Transportation Technologies (OTT), in support of its basic mission statement:

> The Office of Transportation Technologies will work in partnership with the domestic transportation industry, energy supply industry, and research and development organizations to develop and promote user acceptance of advanced transportation vehicles and alternative fuel technologies which will reduce oil import requirements, and reduce criteria pollutant emissions and greenhouse gases. The Office will also develop a strong transportation technology base to enable this industry to assure strong competition in the domestic and world markets.[7]

The study methodology incorporated the following goals:

A. An examination of HEV design options, on the basis of an extensive literature review, discussions with analysts and component and vehicle developers, and technical analysis.

B. Selection of a set of design options for analysis. In particular, our two DOE sponsors, the Office of Transportation Technologies' Planning and Assessment Group and its Office of Technology Utilization, have different interests:

---

[6] This analysis involves, as much as possible, constant technology and comparable performance comparisons of HEVs and conventional vehicles (CVs). Argonne has made use of the Advanced Vehicle Simulator (ADVISOR) model developed by the National Renewable Energy Laboratory (NREL) and, throughout this project, with the participation of D. Bharathan of NREL, has worked with NREL to improve ADVISOR, especially its simulation of CVs.

[7] OTT website, www.ott.doe.gov/ottover.html

- Planning and Assessment is interested in HEVs that closely resemble conventional vehicles and will not rely on grid electricity; all of their energy is obtained from their onboard fuel. These are the type of vehicles being designed by the PNGV.

- Technology Utilization is interested in HEVs that obtain a portion of their energy from the grid and probably will operate part of the time in a pure electric mode.

C. Simulation of the energy use and air emissions of vehicle operation. This task includes development of necessary simulation models; selection of appropriate vehicle driving cycles to simulate real-world driving; analyzing vehicle physical characteristics, such as total weight, engine and battery size, and power (including development of models to calculate these characteristics); and executing the simulation models. The key simulation tool we use is the Advanced Vehicle Simulator, or ADVISOR model, developed by the National Renewable Energy Laboratory. ADVISOR provides estimates of a vehicle's energy use and emissions for a range of driving cycles by calculating the second-by-second forces on the vehicle and the power demanded from each component of the drivetrain, from the tires to the engine, using maps of efficiency, fuel use, and/or emissions for each component. ADVISOR is also capable of doing "forward" calculations starting with throttle behavior and estimating the effect on each drivetrain component in turn, to finally calculate the effect on vehicle movement.

D. Calculation of the purchase and life cycle costs of the vehicles analyzed, as well as exploration of some of the design trade-offs implied by cost considerations.

As of the end of Phase I, we have succeeded in our original goals for A and B and made substantial progress on goals C and D. In regard to goal C, we have found the task of vehicle modeling to be more challenging than we had anticipated. We have worked to overcome a number of problems; including (1) a scarcity of publicly available engine fuel economy and emissions maps, with those available having limited or no data in important operating areas, and (2) limits to the capabilities of the early versions of the ADVISOR vehicle simulation model we began working with. Among other things, the ADVISOR version with which we began did not accept engine maps with negative torque data, it did not inform the user when available engine plus battery power could not match the requirements of the more vigorous driving cycles, and its transmission model caused the engine to operate in an unrealistic fashion. We now are satisfied, for the most part, with our ability to use the upgraded versions of ADVISOR to model vehicle energy use, but we remain skeptical of our emissions results, and so we do not report them here.

For goal D, we have completed but not yet documented a cost and component sizing model, HEVCOST (Hybrid Electric Vehicle Component Sizing and Vehicle Cost Model). We have used the present version of HEVCOST to conduct several cost analyses of conventional and hybrid electric vehicles for this report and will continue to update and modify it.

We intend this report to accomplish the following:

- Present the preliminary results of our vehicle modeling and the necessary background information related to the modeling exercise. Appendix A to

Section 1 describes the basic vehicle designs, component choices, and types of driving we have examined in this phase of the study.

- Describe the modeling improvements we have made, specifically, development of the HEVCOST model that computes, in addition to cost, hybrid vehicle weight and component power characteristics.

- Describe what the study team has learned about hybrid vehicle modeling methodology.

This report is organized as follows:

**Section 2, Hybrid-Electric Vehicles: Theory and Design —** We discuss the energy implications of hybrid systems, the basic types of vehicle designs, and the relationship between design choices and vehicle performance.

**Section 3, Methodology and Modeling Issues**

**Vehicle modeling —** We discuss in detail the models we use (the HEVCOST design model to "build" the vehicle, ADVISOR to cross-check HEVCOST and to simulate vehicle operations) and various methodology issues: choosing control strategies for the vehicles, problems encountered in modeling vehicle operations and the work done toward achieving solutions, and constructing a methodology to project the magnitude of vehicles' use of electricity from the grid when the option of ordinary refueling also exists and competes with electric refueling.

**Estimating the electricity and gasoline use of grid-connected hybrids —** We describe the assumptions and method used for estimating the split between fuel-driven and grid electricity-driven miles for hybrids with grid-connection capability.

**Section 4, Fuel Consumption and Cost Results** (for both CVs and HEVs) — We present a definition of the scenarios analyzed, key caveats, and the vehicle modeling results.

In presenting our results, we have tried to be careful to present fair comparisons of conventional and hybrid electric vehicles. In our experience, many reports describing the benefits and costs of new types of vehicles, e.g., electric vehicles, have failed to account for important differences between the new vehicles and conventional ones or have failed to configure the new vehicles being analyzed in such a way that they fulfill the same functions as the conventional vehicle. Appendix B to Section 1 describes some of the important concerns that arise in comparing different vehicles.

# Section 1 Appendix A
# **At What Types of Vehicles Are We Looking?**

In this phase of the HEVTA, we have examined a series of vehicles designed to be as identical as possible from the driver's point of view. That is, to the extent possible, the driver wouldn't know which vehicle he was driving except when he had to refill (or recharge) the vehicle. In every example, the basic vehicle is a midsized passenger car that retains the same basic platform (the car minus its drivetrain). That is, regardless of whether the vehicle is a conventional vehicle or one of several different types of hybrids, and regardless of its performance, the body structure is identical (exception: the hybrids' 5% greater structural weight accounts for added structure needed for batteries, etc.), the aerodynamic drag coefficient is identical, the assumed accessory load is identical, and the rolling resistance coefficient is identical. Only the drivetrain changes.

Furthermore, although CVs and hybrids will not perform identically, performance is held to be identical or near-identical in some important ways. In particular, vehicles being compared will have either identical Z60 times if they are independent of the grid, or identical Z60 times in at least one mode of operation if the hybrids in the group are grid-dependent and will operate part-time as electric vehicles. Although hybrids with downsized engines will have long-term gradeability inferior to that of their matching CVs, the hybrids are held to minimum standards developed for the Partnership for a New Generation of Vehicles – 55 mph up a 6.5% grade for 20 minutes. Some of the hybrids evaluated here exceed this minimum considerably, but still are not as capable as CVs.

The hybrid vehicles examined in this analysis use nickel metal hydride batteries whose performance is based on existing batteries used in the Toyota Prius (Japanese market version) and RAV-4, and a permanent magnet motor based on a Unique Mobility design.

The components of a hybrid drivetrain can be sized in a number of ways to satisfy performance requirements. The baseline hybrid drivetrain in this analysis is sized by matching engine power to that needed to achieve long-term gradeability, with the motor and battery then sized to allow achievement of the Z60 requirement. This type of design is designated a "full" hybrid in that it produces a vehicle with substantial electric "boost." The engine is considerably smaller than that of the equivalent CV, because the power required for the PNGV gradeability limit is considerably less than acceleration power requirements; generally, the downsizing is of the order of 40% or so for a 12-second Z60 requirement, and somewhat more for more demanding Z60 requirements. We also examine a design with a larger engine and smaller battery and motor, which is designated a "mild" hybrid.

The following types of vehicles are examined:

- Conventional vehicles
- Parallel and series grid-independent full hybrids
- Parallel grid-independent mild hybrids
- Parallel and series grid-connected hybrids

Because high power has been a valuable commodity in the U.S. automobile market, we examine a range of Z60 times for the vehicles. For CVs and grid-independent hybrids we examine 12-, 10-, and 8-second Z60s; for grid-connected hybrids we examine 12-, 14-, and 16-second Z60s in all-electric mode, tested with HEV battery at 0.2 state of charge (SOC).

Hybrid vehicles may employ a variety of strategies to control the use of engine, battery, and electric motor in powering the vehicle. Parallel hybrids, in particular, split the responsibility for driving the wheels between the engine/transmission pathway and the battery/electric motor pathway; furthermore, the engine can be used to recharge the battery. In the parallel hybrid vehicles examined in this phase of the study, we assume that the vehicles are launched electrically (with electricity from the battery) to a preset speed, with the engine off; the engine is then turned on, and power responsibility is then shifted to it, with the motor available to provide a boost if the power demanded exceeds the engine's capability. The engine is automatically turned off when the vehicle is braked or is at idle or coasting. Braking is accomplished with the motor to the maximum extent possible, with electricity generated by regenerative braking fed to the battery. Other strategies are possible, of course, and will be investigated as the study proceeds.

# Section 1 Appendix B
# **What Is a Vehicle?**

It is not difficult to design a vehicle that attains a fuel economy of several hundred miles per gallon; actually, a few thousand miles per gallon is possible under ideal conditions. However, such vehicles have little or no utilitarian value — more than likely, they will accommodate one person (the driver) under extremely confined conditions (lying down inside a lightweight shell to minimize aerodynamic drag and weight); they will have very low power in order to minimize engine size and weight and to ensure that the engine operates generally at an efficient load; they will therefore have minimal performance and, in fact, might have little or no hill-climbing capability and low top speed; they will have no power accessories, and possibly minimal braking capability; and they will offer little or no protection in a crash, again to minimize weight. Although vehicles designed to garner fuel efficiency records may be an extreme example, their example should serve as a warning that vehicle analysis should examine carefully whether vehicle design options satisfy the range of criteria that define a vehicle acceptable to the current or some future marketplace in terms of performance, safety, comfort, and other characteristics.

Vehicle criteria of importance to the marketplace include:

- Performance – range, acceleration capability, gradeability, load-carrying ability, including towing ability, and top speed/cruising speed;
- Emissions – compliance with regulatory requirements;
- Safety – crashworthiness, handling/braking capability, protection from hazardous materials, and compliance with regulatory requirements;
- Moderate purchase cost and operating costs;
- Convenience of refueling;
- Reliability and cost of repair;
- Comfort and convenience, including adequate passenger and storage space, heating and cooling capacity, etc.

Moving to hybrid vehicles raises a number of issues with respect to these criteria:

**Repeatability of performance.** A hybrid's reliance on a battery or other energy storage system of limited capacity to supplement its onboard power unit (OBPU) when maximum power is demanded implies that the vehicle's performance capability may be reduced if the energy storage is depleted or otherwise limited. For example, a hybrid may use its engine to satisfy high power requirements of long duration (high speed cruise, ascent up long grades) and a battery to add supplemental power for rapid acceleration. If a number of rapid accelerations is demanded in quick succession, the battery may offer inadequate power because of charge depletion or overheating. Some hybrid storage devices are especially vulnerable to charge depletion because of their low storage capacity, e.g., ultracapacitors. Thus, a hybrid may offer differing levels of protection against reduced performance caused by depletion of its stored energy, with different implications for the required power capability of the OBPU (Tamor, M.A., 1996, Ford Motor Company, unpublished material).

- Full protection – all operation can be supported by the OBPU acting alone (here, the OBPU's power would have to match the vehicle's maximum power requirement);

- Steady-state protection – all constant-speed operations (high speed cruise, very long grades) can be supported by the OBPU, energy storage supports some transients that do not last long, e.g., accelerating to highway speeds (OBPU power between 60 and 100% of maximum required); both the Prius and Insight hybrids appear to meet this requirement, although the Prius has a dashboard light that alerts the driver to a low SOC in the battery;

- Statistical protection – performance failure can occur extremely rarely, or only in non-normal operations (OBPU power between 30 and 60% of maximum);[8] and

- No protection – performance failure can occur, but vehicle will warn driver before it happens, driver must adjust accordingly (OBPU power less than 30% of maximum) (Tamor 1996).

According to Tamor, vehicle designers will likely avoid both "full protection" because it negates much of the potential efficiency benefit of the hybrid (with no weight savings from the OBPU and the added weight of energy storage and motor), and "no protection" because it is unlikely to be acceptable to drivers. The market viability of statistical protection is not clear, particularly for mass market vehicles.

**Emissions performance.** Aside from their potential to improve vehicle energy efficiency, hybrid configurations have been advocated as a means of substantially reducing vehicle emissions by eliminating or reducing engine excursions into load/speed regimes where emissions are high, reducing engine size, providing time to electrically heat the catalyst before cold starts, accommodating the use of OBPU technologies that are inherently low emitters, and "electrifying miles," as discussed elsewhere. Another potential emissions advantage, not foreseen prior to the commercialization of hybrid vehicles, is rapid catalyst warm-up regardless of driving conditions following start-up. This is characteristic of the new Prius hybrid. On the other hand, some concerns were previously raised about possible emissions surges caused by multiple hot restarts (for hybrids that turn the engine off at idle and low loads, or when the battery reaches a SOC maximum). However, emissions tests have thus far failed to detect significant emissions surges on restart.

[8] Presumably, the vehicle would warn the driver in the rare event of a potential performance loss.

Although both Prius and Insight have excellent emissions performance, it is not clear that the nature of the drivetrain will be the deciding factor in this performance (vehicles with conventional drivetrains have been shown to be capable of extremely low emissions). Hybrids may, of course, be no less invulnerable to control system malfunctions than conventional vehicles, although some hybrid advocates have proposed that the reduced speed/load range (assuming the energy storage will absorb most transient power requirements) of the OBPU will reduce malfunctions.[9]

**Performance in electric vehicle (EV) mode.** Some hybrid configurations can operate for several miles using only their stored energy, with the OBPU off. As discussed elsewhere, this mode might be considered standard operating procedure for the beginning of all trips, or as a special mode for use in EV-only zones or during a gasoline/diesel fuel emergency. The storage device will have to be extremely large or have very high specific power, however, to be able to satisfy vehicle performance criteria expected under full power (OBPU plus storage), so the development of high-specific-power batteries may be crucial to this type of design. The market acceptance of a reduced power mode (if an ultra-high-specific-power battery is not available) is not certain, though clearly it will depend on the circumstances that cause the EV mode to be selected and the precise nature of the performance compromises.

**Safety concerns.** The primary safety concerns with hybrid drivetrains are associated with the specific characteristics of any new drivetrain components that may be added (e.g., high temperature materials in certain battery types, volatility of new fuels, high pressure storage tanks,[10] etc.). In general, however, there appear to be few safety concerns that are unique to hybrid drivetrains.

The PNGV has established a variety of vehicle targets associated with fuel economy and emissions, performance, vehicle dynamics and structure, and other characteristics. A portion of these is presented in Table 1. It is possible that diverse design efforts will tend to coalesce around these targets, because they represent characteristics that are proven in the marketplace. That is, they are designed to match the overall performance of successful conventional vehicles, though with some compromises associated with the characteristics of hybrid drivetrains. It is important to note, however, that the characteristics of the current light-duty fleet have evolved as an interaction between consumer needs and the characteristics of conventional internal combustion engine (ICE) drivetrains. Designers of hybrid drivetrains can squeeze the integrated physical/operating design of their drivetrains to match those of current ICE drivetrains, or they might instead choose, at some market risk, to accept the differences between hybrid and conventional vehicles and design to the hybrid's strengths, accentuating short-term acceleration,

---

9 Although the hybrid's engine will be on fewer hours than a conventional vehicle's engine, and will experience fewer transients, it will be turned on and off considerably more often. The effect on the potential for emission control malfunctions needs to be determined.

10 Although new fuels may be used with conventional drivetrains (i.e., the safety concerns are not specific to hybrids), their use in hybrids may be more likely because hybrid configurations can better accept power plant/fuel combinations that may be ill-suited to conventional use because of their poor static and/or dynamic matching with vehicle power requirements.

for example, at some cost in long-duration gradeability or other characteristic. Only time and market experience will tell which design direction is most likely to succeed.

**Table 1 Selected PNGV Performance Guidelines**

| Vehicle Performance at 77% State of Charge | |
|---|---|
| Peak acceleration | 17 ft/sec$^2$ |
| 0-60 mph accel | 12 seconds |
| 0-85 mph accel | 25 seconds |
| 40-60 mph pass time | 5.3 seconds |
| Maximum speed (minimum) continuous | 85 mph |
| Gradeability, forward & reverse launch | 30% at gross vehicle weight (GVW) |
| Gradeability, forward | 6.5% @55 mph for 20 minutes (GVW w/full accessory load) |

# Section 2
# Hybrid-Electric Vehicles: Theory and Design

## 2.1 Background

Hybrid electric vehicles (HEVs) represent a cross between a conventional automobile and an electric vehicle. They combine an electric drivetrain, including battery or other energy storage device, with a quickly refuelable power source such as a gasoline or diesel engine, fuel cell, or gas turbine. This refuelable power source, called an onboard power unit or OBPU, generally can recharge the storage device and may drive the wheels either directly (as can the electric motor) through a mechanical drivetrain, or indirectly by providing electric power to the motor. If the refuelable source can drive the wheels directly (in parallel with the electric motor), this is a *parallel hybrid*; if the refuelable source's function is to supply electricity to the motor (and to recharge the storage device), with only the motor driving the wheels, this is a *series hybrid***.**

The hybrid concept is by no means a new one. A Woods gasoline-electric coupe selling for $2700 was introduced in 1916. This early hybrid electric vehicle combined a four-cylinder gasoline engine with an electric motor and a battery half the size of those used in contemporary electric cars. Like today's Toyota Prius, it used its electric drive for low speeds and the gasoline engine for higher speeds and to recharge the batteries (Schiffer 1994). Sixty years later, the Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976 authorized the U.S. Department of Energy (DOE) to encourage and support research and development of hybrid vehicles (U.S. DOE 1994). DOE subsequently sponsored major studies beginning in the late 1970s with teams led by the Jet Propulsion Laboratory (JPL) and the Aerospace Corporation. These studies included both in-depth computer simulations of hypothetical vehicles and the design, construction, and testing of prototype vehicles (Burke 1992). The JPL/GE Near-Term Hybrid Vehicle program, which ran from 1978-82, developed a working vehicle, called the HTV-1, with a parallel hybrid drivetrain (Burke 1992).[11]

The target performance of the vehicles contemplated and built in these early programs was between that of conventional gasoline vehicles and electric vehicles of the time, and comparable to the relatively low-powered diesel vehicles then available. The Department of Energy has since embarked on programs that aim to produce vehicles with performance more likely to compete with conventional gasoline-powered vehicles. The Department has pursued both its own research program, the Electric and Hybrid Vehicles Program,[12] and a joint government/industry program, the Partnership for a New Generation of Vehicles (PNGV), initiated in 1993 by the

[11] At the time this vehicle was built, the available motors, controllers, and inverters were much heavier than those available today. The 80-90 kW that would have been demanded with a series configuration — which demands considerably more power in the electric drivetrain than does a parallel configuration — would have been difficult to package.

[12] Established in response to the Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976.

U.S. government and the United States Council for Automotive Research (representing Chrysler, Ford, and General Motors). The PNGV's primary goal is to develop a fully competitive family car with fuel economy up to 3 times current levels; the PNGV research team has settled on a hybrid drivetrain as an integral part of this vehicle.

The DOE and PNGV have been driven largely by concerns about oil savings. Interest in hybrid vehicles stems also from the State of California's Zero Emission Vehicle (ZEV) requirements, which demand that automakers doing business in California begin producing substantial quantities of ZEVs within the next decade.[13] The ZEV requirements are driven by air quality concerns, and the California Air Resources Board (CARB) proposes allowing hybrids to attain partial ZEV credits (that is, each hybrid vehicle will be counted as a fraction of one electric vehicle). The previous version of the ZEV proposals were as follows (Air Resources Board 1999):

- The vehicle must first meet Super ultra low emissions vehicle (ULEV) emissions requirements[14] at 150,000 miles, to establish a base 0.2 allowance
- A qualifying vehicle accumulates additional allowance above 0.2 if it:
  - Has a zero emission range of 20 miles (0.3 allowance) to 100 miles or more (0.6 allowance)
  - Within its zero emission range, employs a strategy to maximize grid recharging (0.1 allowance, but total ZEV range allowance is limited to 0.6)
  - Uses fuel with inherently low fuel cycle emissions (up to 0.2 allowance)
  - Employs advanced ZEV componentry (e.g., advanced batteries) but doesn't otherwise qualify for zero emission range credits (0.1 allowance).

Under this system, a Super ULEV hybrid with a 20-mile ZEV range and some mechanism to maximize grid recharging would earn an allowance of 0.2+0.3+0.1 = 0.6. The ZEV system is currently being modified, with potential provisions including a reduction in the minimum electric vehicle (EV) range for a grid-connected hybrid, and initial award (e.g., for 2002) of 1.8 credits for a 20-mile range grid-connected hybrid.[15]

[13] The original requirements demanded that 2% of vehicles offered for sale would be ZEVs by 1998, with the percentage rising to 10 by 2002. The 1998 requirement was eliminated, and the 2002 requirement is being reconsidered.

[14] Including zero evaporative emissions, meeting onboard diagnostic requirements for 150,000 miles, and extending emission controls warranty (including the battery warranty) to 150,000 miles.

[15] Personal communication, Chuck Shulock, Air Resources Board, 8/22/2001.

More recently, interest in hybrids has also been driven by concerns about global warming. Hybrids' increased fuel efficiency and their enhanced potential to use alternative fuels (see discussion in Section 2.3) may yield significant reductions in emissions of carbon dioxide, the key greenhouse gas.

## 2.2 Energy Use in Conventional Vehicles

To understand how a hybrid may save energy, it is necessary first to examine how conventional vehicles use energy:

In order to maintain movement, vehicles must produce power at the wheels to overcome aerodynamic drag (air friction on the body surfaces of the vehicle, coupled with pressure forces caused by the air flow), rolling resistance (the resistive forces between tires and the road surface), and any resistive gravity forces associated with climbing a grade. Further, to accelerate, the vehicle must overcome the natural resistance of its mass to acceleration, called inertia – most of the energy expended in acceleration is then lost as heat in the brakes when the vehicle is brought to a stop.[16] And in addition, the vehicle must provide power for accessories such as heating fan, lights, power steering, and air conditioning.

Finally, a vehicle will need to be capable of delivering power for acceleration with very little delay when the driver depresses the accelerator, which may necessitate keeping the power source in a standby (energy-using) mode.

A conventional engine-driven vehicle uses its engine to translate fuel energy into shaft power, directing most of this power through the drivetrain to turn the wheels. Substantial amounts of energy are lost along the way. Within the engine, for example, moving parts – especially pistons, crankshaft, and valves – create friction; there are a number of aerodynamic and fluid drag losses ("pumping losses") because air must be pumped through air cleaner, intake manifold, valves, and exhaust system, and, most importantly, because spark-ignition engines reduce their power output by throttling the air flow which causes additional aerodynamic losses that are very high even at light loads. Much of the heat generated by combustion cannot be used for work and is wasted, both because heat engines have theoretical efficiency limits, and because attaining even these limits is impossible because some heat is lost through cylinder walls before it can do work, and some fuel is burned at less than the highest possible pressure (OTA 1995).

Fuel is also burned while the engine is experiencing negative load (during braking) or when the vehicle is coasting or at a stop, with the engine at idle.

Although part of engine losses would occur under any circumstances, part occur because in conventional drivetrains, engines are sized to provide very high levels of peak power for the acceleration capability expected by consumers[17] – perhaps 10 times the power required to cruise

[16] Some of this energy is also lost as aerodynamic drag and rolling resistance losses.

[17] For a mass market family car in today's market, the ability to accelerate from 0 to 60 mph in 12 seconds may be a minimum capability.

at 60 mph – but are operated at most times at a small fraction of peak power where they are quite inefficient. Having such a large engine also increases the amount of fuel needed to keep the engine operating when the vehicle is stopped or during braking or coasting, and increases losses due to the added weight of the engine, which increases rolling resistance and inertial losses. Even gradeability requirements (example: 55 mph up a 6.5% grade) require only about 60 or 70% of the power needed to accelerate from 0 to 60 mph in under 12 seconds.[18] Multispeed transmissions allow the engine to operate within a fairly narrow speed regime across the range of vehicle speeds, allowing the engine to stay in the most efficient parts of the engine map more of the time than would be the case with fewer gears – but at the cost of losses in the transmission itself.

Figure 2-1 shows how fuel energy is translated into work at the wheels for a typical midsize vehicle in urban and highway driving as represented by U.S. Environmental Protection Agency (EPA) driving cycles.[19] The part of the figure at the right represents the tractive losses incurred by the vehicle as a fraction of the total fuel energy. Some highlights of the figure are:

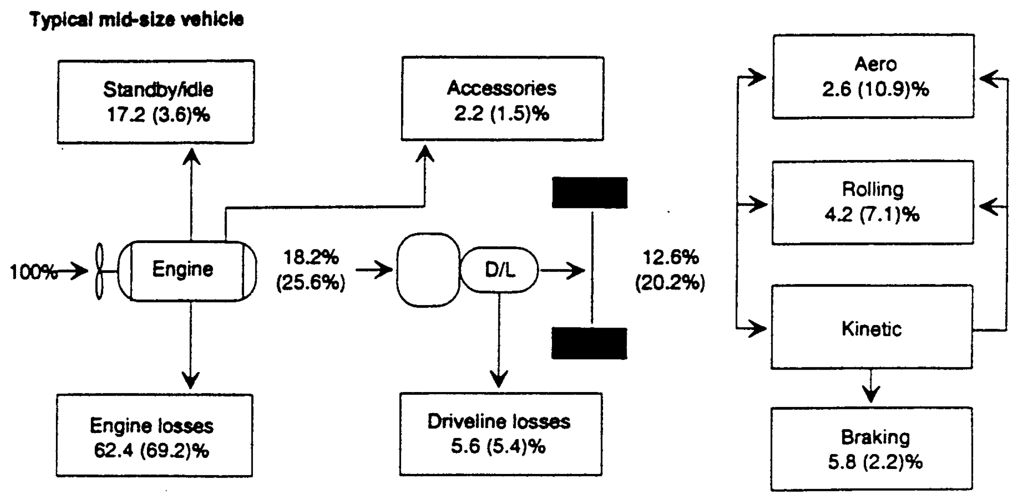
- At best, only one-fifth of the fuel energy reaches the wheels and is available to overcome the tractive forces, and this is on the highway cycle when idling losses are at a minimum, braking loss is infrequent, and shifting is far less frequent.

- Braking and idling losses are extremely high in (EPA cycle) urban driving and even higher in more congested driving, e.g., within urban cores during rush hour. Braking loss, that is, the shedding of the kinetic energy of motion through heat generated by the brakes, represents 46% of all tractive losses in urban driving. Idling losses represent about one sixth of the fuel energy on this cycle.

- Losses to aerodynamic drag, a fifth or less of tractive losses in urban driving, are more than half of the tractive losses during highway driving.

[18] Depending on relative inertia and other losses and on the vehicle load specified for both acceleration and gradeability requirements.

[19] Note that the box labeled “kinetic” represents the potential energy built up in accelerating the vehicle. This energy is lost as heat in braking and in the rolling and aerodynamic losses that occur as the vehicle decelerates. In other words, regenerative braking’s “target” for recapture is not the full potential energy of the vehicle, because rolling resistance and aerodynamic drag will always be responsible for part of the braking forces when the vehicle is slowed. Another factor that can limit the amount of kinetic energy recoverable is the number of axles driven. For safety, both axles must brake, so only four-wheel drive cars can target the full braking energy. Front-wheel drive cars fare a bit better than rear-wheel drive cars because, in most cars, the front brakes do the larger share of the braking.




NOTE: Numbers indicate urban energy distribution. Numbers in paretheses indicate highway energy distribution.
SOURCE: Partnership for a New Generation of Vehicles.

**Figure 2-1 Energy Flow (from fuel energy to power at the wheels) for a Midsize Automobile**

## 2.3 Energy Savings Potential of Hybrid Drivetrains

In terms of overall energy efficiency, the conceptual advantages of a hybrid over a conventional vehicle are:

- **Regenerative braking.** A hybrid can capture some of the energy normally lost as heat to the mechanical brakes by using its electric drive motor(s) in generator mode to brake the vehicle;

- **More efficient operation of the onboard power unit (OBPU), including elimination (or sharp reduction) of idle.** A hybrid can avoid some of the energy losses associated with engine operation at speed and load combinations where the engine is inefficient by using the energy storage device to either absorb part of the OBPU's output or augment it (or even substitute for it), allowing it to operate only at speeds and loads where it is most efficient. When an HEV is stopped, rather than running the engine at idle, where it is extremely inefficient, the control system may either shut off the engine, with the storage device providing auxiliary power (for heating or cooling the vehicle interior, powering headlights, etc.), or run the engine at a higher-than-idle (more efficient) power setting and use the excess power (over auxiliary loads) to recharge the storage device. When the vehicle control system can shut the engine off at idle, the drivetrain can be designed so that the drive motor also serves as the starter motor, allowing extremely rapid restart due to the motor's high starting torque.

- **Smaller, lighter OBPU.** Because the storage device can take up part of the load, a hybrid's OBPU can be downsized. In some cases, the OBPU can be sized for the highest sustained loads, not for (higher) short-term acceleration loads. Consequently, the OBPU can have a significantly lower power rating than the engine in a conventional vehicle. This allows the engine to be run at a higher fraction of its rated power, generally at higher efficiency, during most driving. Also, the reduced engine weight is mildly beneficial to fuel economy.[20]

- **Potential for alternative OBPU technologies.** Conventional drivetrains use piston engines because such engines do a fair job, when coupled with multispeed transmissions, of efficiently matching vehicle load requirements (static matching), and an excellent job of rapidly boosting or reducing power to match the vehicle's changing loads (dynamic matching). Most alternative power sources do not share these matching characteristics. For example, turbine engines are extremely inefficient at the low loads typical of normal driving, and are slow to respond to changing load, but they can burn a wide variety of fuels and are small and lightweight in relationship to their power output. In a hybrid drivetrain, the storage device could assume the load-following role, compensating for the turbine's slow response, and allow the turbine to operate in a high output, efficient mode by absorbing its excess energy output. Remaining roadblocks for turbines include high $NO_X$ emissions at high loads and the need for further development of the ceramic materials used to increase their efficiency.

There are counterbalancing factors reducing hybrids' energy advantage, including:

- **Potential for higher weight.** Although the fuel-driven energy source on a hybrid generally will be of lower power and weight than the engine in a conventional vehicle of similar performance, total hybrid weight is likely to be higher than the conventional vehicle it replaces because of the added weight of the storage device, electric motor(s), and other components. This depends, of course, on the storage mechanism chosen, the vehicle performance requirements, and so forth. The hybrid configurations examined in this report [conventional internal combustion engines (ICEs) and nickel metal hydride batteries] were consistently heavier than their conventional vehicle (CV) counterparts.

- **Electrical losses.** Although individual electric drivetrain components tend to be quite efficient for one-way energy flows, in many hybrid configurations, electricity flows back and forth through components in a way that leads to cascading losses. Further, some of the components may be forced to operate under conditions where they have reduced efficiency. For example, like ICEs, most electric motors have lower efficiency at the low-speed, low-load conditions often encountered in city driving.[21] Without careful component selection and a control strategy that minimizes electric losses, much of the theoretical efficiency advantage often associated with an electric drivetrain can be lost.

[20] Although, as discussed below, this weight benefit will likely be more than offset by the weight of the electric drivetrain components.

[21] With parallel hybrids, the motor may be quite small, so that low-speed "low *vehicle* load" conditions may actually be fairly high load when measured against the motor power rating.

## 2.4 Emissions Trade-Offs

Because hybridization changes the way a vehicle's engine is operated, emissions performance should change as well. For the most part, hybrid features seem to offer several advantages in controlling emissions: the power available from the electric motor can help keep engine operation away from high-emission regions; engine downsizing will mean that normal vehicle loads will be at a higher percentage of engine rated power (which is generally more efficient and less polluting) than in a conventional drivetrain; the power absorbing capability of the battery allows the engine to be run in a startup mode that shortens the cold start period, reducing starting emissions; and electric heating of the catalyst is more feasible than in a conventional drivetrain. One early emissions concern with hybrid operation was the possibility of emissions spikes from multiple hot and warm restarts. Many of the hybrid powertrain control strategies discussed by researchers envision the engine being turned off and restarted several times during a trip. For example, some hybrids will have electric launch, with the engine turned on only when the vehicle reaches a predetermined speed or when total vehicle load reaches a predetermined level; this strategy is used in the Prius. Also, both Prius and Insight, and probably most future hybrids, will use "idle off," where the engine is shut down during a stop (it can also be shut down during braking and coasting). The engine is then restarted when positive torque is demanded (or when a minimum speed is attained after a stop). Thus far, the excellent emissions performance of both Prius and Insight imply that the concern about emissions spikes may not be a problem, although it is worth further study.[22] It is worth noting that the high level of control of engine operation available in a hybrid can also help prevent emissions spikes, for example, the Insight's control system uses the electric motor to bring engine rpm up to operating levels *before* injecting fuel during an engine restart, reducing the possibility of any emissions spike.[23]

In hybrids with substantial all-electric range, the capability to operate in a zero emission mode yields emissions advantages whether or not the battery is recharged by the grid or by the vehicle's own engine. The ZEV capability can allow dramatic changes in the amount, timing, and location of emissions that might be used to advantage to improve air quality. The key advantages are locational and temporal:

- *Locational*. This type of hybrid can operate, at least for a time, in an electric vehicle (EV) mode within a dense urban core. With grid recharge, the recharge electricity may be generated at a power plant quite distant from the urban area. Engine recharge for at least a portion of these vehicles will occur outside of the core (for example, a suburban-based hybrid might switch its engine off on entering the core, and restart it when it returns to the suburbs in the evening).

[22] Highly sophisticated emissions measurement technology, allowing detailed study of emissions variation on a virtually instantaneous basis, has become available in the last few years. This is the type of technology needed to examine issues such as emissions spikes after warm restarts, and Argonne National Laboratory currently is using this technology to examine the emissions trade-offs made possible or caused by hybridization. Industry is undoubtedly conducting similar research.

[23] Personal communication, John German, Honda North America.

- *Temporal*. For many areas, there is a theoretical advantage to having vehicle emissions shifted from early morning to late afternoon because of the role of sunlight in producing smog. Hybrids with substantial EV range may be able to operate in EV mode during the morning commute or in other morning driving, switching their engines on only in the afternoon when emissions may have less impact on ozone concentrations.

We stress that the temporal advantage is theoretical because, to the best of our knowledge, no air quality modeling research has been conducted to verify that a shift of morning emissions to the afternoon will provide an ozone air quality benefit. Results should vary depending on whether the battery recharge for the ZEV operation comes from the grid or from afternoon (or overnight) engine recharging. Results will also depend strongly on the location and emissions properties of recharging power plants and on the specific ozone formation chemistry of the air basin where the vehicles are operating.

## 2.5 Elements of Hybrid Design

In hybrids, the major design choices involve selecting the type and size of OBPU, motor/generator, storage device, and other components, and designing an operating strategy that directs the operation of the components and channels energy flows through the drivetrain.

Although there are numerous ways to configure a hybrid drivetrain and a variety of ways to characterize various groups of hybrids, dividing hybrids into series and parallel types is an obvious first-order characterization, and the one adopted here to describe the design choices associated with hybrids.

### 2.5.1 Parallel Hybrids

In parallel hybrids, both the OBPU and the electric motor(s) can drive the wheels, either separately (each takes one drive shaft), or through a transmission or gear set with two or more input shafts, or through use of an integrated motor/engine set where the motor can also serve as the starter. Figure 2-2 shows a simplified layout of a parallel hybrid with engine and battery/electric motor(s) powering separate driveshafts. A commonly discussed mode of operation for parallel hybrids has the vehicle operating like an EV at low speeds, with only the motor(s) engaged (this is called electric launch); the OBPU engages only at higher speeds. This operating strategy keeps engine operations away from low load operations that generally produce high hydrocarbon (HC) and carbon monoxide (CO) emissions and inefficient fuel use. Within this basic design, there are a number of choices of alternative operating strategies. For example, one operating strategy would limit motor usage to electric launch, regenerative braking, and power boosting when the OBPU could not handle the power demand by itself. In other words, once the OBPU is engaged after an electric launch, it would provide all of the power needed to run the vehicle, with the motor disengaged except during braking (to be used as a generator for regenerative braking) or under high load (e.g., during high acceleration) to provide boost power to the engine. When the vehicle is stopped, the engine can be turned off and the accessories run by the battery. Toyota’s Prius HEV operates this way. Although Toyota calls the Prius a “parallel/series” hybrid, from the basis of energy flows it may be most appropriately called a parallel hybrid.

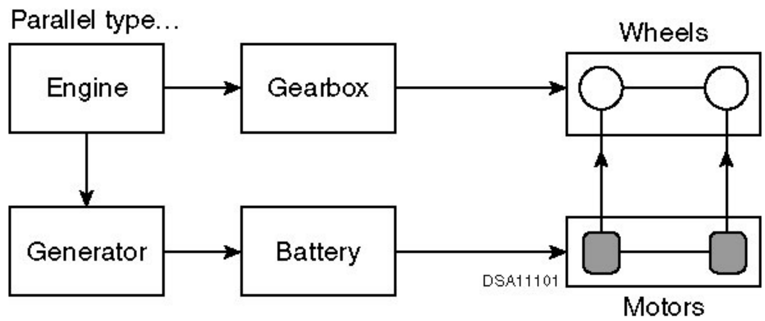



**Figure 2-2  One Example of a Parallel Hybrid Drivetrain**

An alternative operating strategy is to use the motor as a more frequent supplement to the engine, to smooth transients or keep the engine out of operating regions where it is less efficient or likely to generate higher emissions. To maximize efficiency, the vehicle control system could be programmed to allow the motor to supplement the engine whenever its net “round trip” efficiency (including battery charge and discharge efficiency, motor efficiency, etc.) exceeded that of the engine pathway. Refinements of this strategy would smooth the load by allowing the engine to lag the instantaneous load by a short time interval and respond to the time-averaged load, with the storage device providing either the power boost or power absorption function as needed to satisfy the instantaneous load. This strategy reduces the transient losses but increases battery losses compared to the instantaneous load-follower (Cuddy and Wipke 1996).

An alternative, sometimes called a mild hybrid system, is to use the motor only as a power booster and for regenerative braking, with no “all-electric” operation; in this case, the motor and storage device may be relatively small and thus less expensive, but there is less opportunity to keep the engine out of less-efficient operating regions and lessened capability for recapturing braking energy. The Honda Insight HEV fits into this category.

Until fairly recently, parallel hybrid designs had generated less interest than series hybrid designs among automakers and researchers, perhaps because they are harder to design and analyze. A parallel hybrid operating in the city will have to turn its OBPU on and off frequently, and smoothly and efficiently combine the changing torques of OBPU and motor, decoupling and recoupling one or the other from the driveshaft when needed (Burke 1992) – not an easy task for either the control system or the transmission.

Although series hybrids are mechanically simpler than parallel hybrids and would seem to be easier to design, an important advantage of the parallel hybrid is that it can obtain the efficiency advantages of the series hybrid (use of regenerative braking, engine downsizing, and maintenance of OBPU operations in the better parts of its operating map) with a more efficient connection of OBPU shaft power to the wheels. In other words, the combination of transmission, torque converter, and differential is more efficient than the series hybrid’s shaft-to-wheel path of generator/alternator, (possibly) inverter, motor/controller, transmission or reduction gear and (unless direct drive wheel motors are used) differential. Another major advantage is that a parallel hybrid’s electric motor will be significantly smaller than that required on a series hybrid, since in the series case the motor provides the sole motive power to the wheels. This yields a significant cost savings. Because most conceptions of the parallel hybrid have the engine doing more load-following than in a series layout, and the engine being frequently turned on and off, there had been concerns that attaining low emissions might be substantially more difficult than with a series layout (Burke 1992). As noted above, this concern now appears to have been misplaced.

Toyota's and Honda's recent successes with the Prius parallel/series hybrid (Toyota) and Insight parallel hybrid (Honda) indicates that anticipated barriers are not insurmountable. Both vehicles attain low emissions, high fuel economy, and smooth operation. Good design and the rapid advances in onboard computing capability appear to have overcome the parallel system's operational complexity.

### 2.5.2 Series Hybrids

In a series hybrid, the OBPU drives a generator, whose electrical output powers an electric motor driving the wheels and any accessories when needed, and charges a storage device when the device's state of charge (SOC) drops below a desired range. Figure 2-3 shows a simplified[24] diagram of a series hybrid layout.

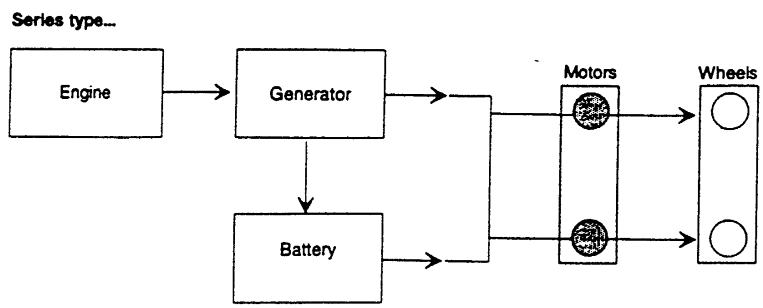



**Figure 2-3 One Configuration of a Series Hybrid Drivetrain**

In a series configuration, all of the tractive power needs are met by the motor, which obtains electricity from either the engine/generator directly or from the battery. As with the parallel hybrid, the control system must decide how to trade off the operating advantages and disadvantages of the various energy paths available to the system – in this case, the "engine to generator to motor" path and the "battery to motor" path, with the battery being recharged from the engine, regenerative braking, and for grid-connected hybrids, the grid. For a grid-independent hybrid, frequent use of the battery to drive the motor may force the engine to recharge the battery, which adds the battery's in/out charging losses to the engine to motor path; the control system will generally avoid engine recharge unless battery charge is getting dangerously low or the engine would otherwise be forced to operate quite inefficiently. But in a grid-connected

[24] Missing are inverters and controllers; if alternating current (ac) motors are used, an alternator could be used in place of a generator (with an inverter between the alternator and battery).

hybrid, the system will often favor the battery to motor path, to maximize the amount of grid-recharging that can be obtained.

### 2.5.3 Component Sizing

The size of the powertrain components, that is, their rated peak and continuous power and, where applicable, energy storage capacity, depends on the basic operating strategy of the powertrain, vehicle characteristics that determine loads (vehicle mass, aerodynamic efficiency, tire efficiency), and performance requirements established for the vehicle, e.g., requirements for minimum Z60 time.

#### 2.5.3.1 A Dated "Thermostat" Concept

We should first clear up a common misperception of what a hybrid will look like. A common early conception of a hybrid was of a vehicle with a small engine operating at a constant output, at its maximum efficiency design point, providing the average energy needed by the vehicle, with a battery (or flywheel or ultracapacitor or other storage device) acting as a load follower, providing any power needed above the average load (e.g., for acceleration or hill-climbing) and absorbing excess engine power when the power needed was below the average load (e.g., during idle or moderate speed cruise).

One problem with this conception is that some trips are made under higher-than-average load conditions for long time periods, e.g., trips with the vehicle heavily loaded, at very high speeds, and/or with significant uphill grades. Consequently, to be able to handle such trips, the engine output power for the hybrid described above would have to be much higher than "average," or else the storage device would have to be large enough to provide the extra power needed without losing its charge – an expensive proposition.

In fact, the performance requirements for normal vehicles make this type of thermostat/constant engine power operation impractical. In the U.S. market, conventional light-duty vehicles are high performance vehicles, satisfying, virtually without exception, a number of demanding standards for acceleration performance, gradeability (hill-climbing ability), sustained high speeds, and long range. For example, the requirement for gradeability (e.g., 55 mph up a 6.5% grade) demands the sustained use of power (under PNGV requirements, for 20 minutes) well above the average encountered in normal driving. Operating constantly at its "best efficiency" point, an engine capable of satisfying gradeability requirements by itself would likely have to be larger than the engine in the conventional drivetrain it replaced (OTA 1995; Murrell 1995).[25] Thus, obtaining the hoped-for small engine requires either that the thermostat strategy

[25] For a midsized auto with a Z60 time of about 12 seconds and gradeability of 60 mph at 6-percent grade with 2 passengers, gradeability requires about 60% of acceleration power (OTA 1995). For a group of modern 4-valve engines, power at the maximum efficiency point averaged 40% of peak power, with a range from 20 to 68%; for 2-valve engines, maximum efficiency power averaged 50% of peak power, with a 35-71% range (Murrell 1995). Assuming a 40-percent maximum efficiency point and a 60-percent gradeability point implies that a constant speed engine in a hybrid drivetrain, operating at its best efficiency point, would have to be rated at 50-percent higher power than the engine in the conventional drivetrain it replaces.

be abandoned and the engine be allowed to follow the load up to its full rated capacity (with some cost in efficiency and emissions performance), or that the storage device be capable of supplying the extra power needed.

Incorporating a battery large enough to provide substantial power assist to the engine over long periods would not be easy. Currently available batteries are capable of providing their peak power only for short periods, because they generate a great deal of heat on rapid discharge. Although batteries could simply be made large enough to provide adequate power for gradeability on a sustained basis (at well below their peak capacity), the trade-off in size, weight, and cost for most batteries would be unacceptable. Some recent battery designs appear to combine reasonable energy storage capability with very high specific power, which might help to solve this problem; however, these batteries are just beginning to become commercially available.[26] Storage devices such as ultracapacitors and flywheels can provide high power more readily than batteries of equal size and weight, but they generally have low specific energy, so that anything but a very large device would have limited capability of sustaining a long hill climb or other extended-duration high power episode. Unless drivers are willing to accept substantial deterioration of performance on such occasions, a design that requires battery power assist for extended events like hill climbing will not be commercially feasible.

#### 2.5.3.2 Grid-Independent Hybrids

Given the impracticality of the small "average power" engine, how should the powertrain components of a hybrid be sized? Although various combinations of engine/battery/motor size will work, one obvious starting point is an engine sized to *at least* satisfy gradeability requirements, since the long duration of these requirements implies that we may not want to rely on battery power to satisfy them. For the case examined by OTA (midsized car, lightly loaded gradeability of 60 mph up a 6% grade, zero to 60 mph acceleration (Z60) time of 12 seconds), a hybrid vehicle engine sized to just meet the requirements would have about 60% of the peak output of the conventional engine drivetrain it replaces (OTA 1995; Murrell 1995). The battery and motor would then be sized to allow the vehicle to meet acceleration requirements, which typically are considerably more demanding in terms of maximum power than the gradeability requirements.[27]

One way to operate this grid-independent drivetrain is to allow the control system to select whatever combination of engine, motor, and battery output satisfies a preselected objective – highest net efficiency, lowest emissions, etc. Selecting as an objective the minimization of energy use is likely to result in the engine following the load above a minimum load, thereby keeping engine operations away from low load operations that generally produce inefficient fuel use and high emissions. At loads below the minimum (for example, during braking or an actual stop, or low speed cruise), either the engine would be shut off and the storage device would

---

[26] As discussed in Section 3, new NiMH battery designs have shown substantial increases in specific power, with batteries in Toyota's Prius hybrid attaining nearly 500 kW/kg.

[27] Motors have both continuous and peak power ratings because of cooling limitations. For acceleration requirements, the motor's peak rating can be used.

power the vehicle, or the engine would be run within its most efficient region (which would produce more power than demanded by the vehicle) and the storage device would absorb the engine's excess power. At loads above the engine's rated power, or above the engine's efficient operating region (for example, during rapid acceleration), the storage device would supplement the engine. This operating strategy seeks to use the storage device only when its net “round trip” efficiency is greater than that of the engine-to-wheels pathway.

This basic type of design (engine sized to provide hill-climbing capability, storage device sized to provide boost power for short-term acceleration) is, of course, not the only design option. For example, if time limits are placed on the requirement for continuous power for grade climbing, such as the PNGV-specified 20 minutes, the storage device might provide a portion of this power, leading to a design with a higher power storage device (with possibly higher storage capacity as well) and smaller engine.[28] Recent development of high power storage devices with good energy density[29] make this option appear more feasible.

In a parallel system, another alternative design, a “mild hybrid,” would be one in which the engine was more powerful and the motor and storage device less powerful, so that the motor/storage device provided only some boost power and a smaller regenerative braking capability as well as the ability to turn the engine off during idle or braking. This type of design represents a trade-off of fuel economy boost versus cost. Using a larger engine will reduce the fuel economy boost of the hybrid, but at a savings in vehicle cost – the battery/electric motor portion of the drivetrain is more expensive, on a marginal $/kW basis, than the engine/ transmission portion of the drivetrain.

#### 2.5.3.3 Grid-Connected Hybrids

An alternative advocated by some – especially those seeking to maximize zero emissions capability – is to design the vehicle as a full performance electric vehicle, with an engine to provide extended range. This vehicle could run in a pure electric mode on days when its total miles traveled were below its all-electric range, or for the first portion of daily travel on days with longer travel (or during some intermediate portion of the travel, if this is advantageous). The number of miles thus electrified then would be primarily a function of the size and specific energy and power of the storage device. For storage devices with substantial energy storage (and thus high all-electric range), most drivers might use the engine only rarely, recharging the storage device each night. To assure full performance on extended-length trips, however, the engine would have to have as much power as the “power booster” engine above.[30] For designs with

[28] Note, however, that there would be a theoretical possibility that such a design would occasionally deplete its reserve storage capacity, forcing the vehicle to “limp home” in an engine-only mode.

[29] The original Japanese version of the Toyota Prius hybrid had NiMH batteries attaining approximately 500 kW/kg specific power and 45 Wh/kg specific energy (Hermance 1998). The 2000MY U.S. Prius has a redesigned battery pack achieving a 880 W/kg specific power (Toyota 2000).

[30] That is, sized for gradeability on engine power alone. On a long trip, the battery would eventually be substantially depleted, and would then be incapable of providing a lengthy power boost for a long grade.

enough EV range to allow the majority of miles traveled to be "fueled" by the grid, the engine's size and weight would be more important considerations than its fuel efficiency; a small, lightweight gas turbine or two-stroke spark ignition (SI) engine might be a good choice for such designs.

The advantages of a grid-connected hybrid include:

- The vehicle can operate in zero emissions mode for a considerable distance, allowing entry to areas that might otherwise be restricted to conventional vehicles and providing a substantial emissions benefit over a grid-independent hybrid.

- It can use grid electricity for a significant fraction of its total travel, reducing gasoline use.

- In the event of an oil crisis, it could be used as a short-range EV, providing transportation capability and thus supplementing domestic oil supplies.

The key disadvantage is that the design will be substantially more expensive than a grid-independent hybrid – the increased battery size and, for parallel designs, increased motor size[31] dictate considerable additional costs with no offsetting reduction in engine requirements.

An important design point for grid-connected hybrids is the relationship between battery longevity and the operating SOC range of the battery during hybrid operation. After the vehicle has traveled its full EV range and the engine is turned on, the control system will seek to maintain battery charge within a predetermined range as the vehicle operates in hybrid mode. The lower this range is, the more grid electricity can be used, since the amount of grid recharge is proportional to beginning SOC minus ending SOC. However, there is some possibility that battery longevity may suffer if the operating range is too low. Vehicle designers must select an operating range based on trading off the potential for more grid recharging versus the (potential) loss of battery longevity at lower SOC operating ranges.

As discussed in Section 2.1, the State of California Air Resources Board has specified that hybrid vehicles with substantial EV range can obtain ZEV credits toward vehicle manufacturers' ZEV goals – an added advantage of a grid-connected design.

#### 2.5.3.4 Limited Performance Hybrids

Relaxation of requirements for full performance and range equivalence allows more flexibility in vehicle design, though perhaps at the cost of reduced consumer satisfaction. For example, a hybrid designed to operate as a full function EV (often referred to as a "range extender") could use an engine sized only to allow high speed cruise capability, forgoing full gradeability for longer trips to minimize engine size and weight (and cost) and maximize fuel

[31] To allow reasonable performance in EV mode.

efficiency.[32] Similarly, relaxing gradeability requirements for a grid-independent hybrid could allow the engine to be considerably smaller, with the improved fuel economy this implies. If the Z60 requirement were retained, however, the vehicle designer would have to either retain the larger engine or install a larger, more powerful battery and motor, at considerable added cost.

### 2.5.4 Role of Component Efficiency

In hybrid-electric powertrains, the engine is used as a generator of electricity (its only role for series hybrids) and producer of power that flows to the wheels through a transmission (parallel hybrids only). When engines are used for electricity generation, their shaft power turns a generator or alternator, producing electricity that flows either directly to the electric motor(s) (which turns the wheels through direct drive, reduction gears, or a transmission) or to the storage device, where it is stored for later use. When the motors are used for braking, they produce electricity that must be stored by the storage device, also for later use to power the vehicle. When battery storage and alternating current (ac) motors are used, the electricity flowing from the engine to either the motors or battery must be inverted, since the battery requires direct current (dc) and the motors, ac; and flow from the battery to the motors must be inverted to produce the required ac. Similarly, electricity produced by ac motor braking would have to be inverted before being stored by the battery, then inverted again later when it is required for use by the motor. Consequently, the hybrid drivetrain's "electric path" from the engine shaft to the wheels loses energy in the alternator or generator, inverters (if needed), motor/controller acting both as motor and as generator/alternator, reduction gear or transmission, and storage device (in both charging and discharging as well as storage). Generally, the "electric" pathway from engine to motor (partly direct, partly through the storage device) is less efficient than the mechanical pathway of transmission, differential, etc. it complements (in a parallel hybrid) or replaces (in a series hybrid). The hybrid gains its advantage from regenerative braking, the smaller engine operating in a more efficient mode than the engine it replaces, and the elimination of idle fuel flow. However, the need to obtain relatively high energy efficiencies from each of the components in the hybrid drivetrain is obvious if hybrids are to attain fuel economy superior to conventional vehicles, even with these latter advantages.

Each component in the drivetrain can use alternative technologies with significant variation in efficiency, cost, size, and weight. Because most batteries have relatively poor in/out efficiency – 80% is typical for a lead acid battery – hybrids with battery storage should be designed to minimize production of excess electricity from the engine that must be stored. This can be translated into a maxim that average engine output should be the minimum possible consistent with the need to maintain reasonable levels of engine efficiency (which may fall off dramatically at light load). Were batteries to be developed with much higher in/out efficiency – DOE has measured 1998 SAFT America Li-ion batteries designed for power-assist hybrids at 93% in/out efficiency (Sutula et al. 2000), for example – the need to minimize use of the storage pathway would diminish.

[32] If grade climbing requirements were anticipated in advance, the engine could be turned on early to maintain charge and allow the vehicle's gradeclimbing ability to be sustained longer.

The efficiency of capture of regenerative braking is also controlled by component efficiency as well as design choices. Assuming four-wheel braking for safety, a portion of braking energy will be lost if the vehicle has two-wheel drive, since only the powered wheels can capture braking energy. Since the motor(s) can exert braking force equal only to their horsepower, a portion of the energy exerted during hard braking will be lost to the mechanical brakes,[33] and a fraction will be lost to the motor gearing or transmission. And a fraction of that captured by the motor/generators (alternators) will be lost at the battery and possibly in inversion to dc power and back again to ac.

### 2.5.5 Trends in Hybrid Efficiency over Time

Over time, improvements in component technology and substantial redesign of some key hybrid system elements, particularly engines, should yield improved efficiency. Ongoing research efforts in electronic components and electric motors should yield important improvements in component efficiency as well as reductions in component size and weight, both yielding improved vehicle efficiency. Further, if hybrid sales grow to sufficient levels, vehicle manufacturers will substitute engines specifically designed for hybrid service for the off-the-shelf designs that dominated early prototypes. Note again that the Prius engine was purposely built for hybrid operation, with a unique combination of Atkinson Cycle design and lightened components to take advantage of its restriction to operating below 4,500 rpm (Toyota 2000).

On the other hand, it is far from certain that hybrid drivetrains' *incremental* improvement over baseline conventional drivetrains will grow with time, and it may shrink. This is because many ongoing improvements to conventional drivetrains focus on reducing the same inefficiencies that hybridization addresses. For example, variable valve timing and lift systems and cylinder deactivation – found in the Mitsubishi MIVEC system and being introduced in other engines – dramatically cut pumping loss, leaving less energy waste for a hybrid drivetrain to reduce. If direct injection stratified charge (DISC) engines are introduced to the U.S. market (they currently are attaining a substantial share in the Japanese market) in the future, the waste "target" for hybrid drivetrains to help reduce will shrink further. In the OTA study, for example, a midsized vehicle was examined for three timeframes (1995, 2005, and 2015) in both series hybrid (with advanced lead acid battery) and "advanced conventional" form where vehicle designs were identical in all aspects except the drivetrain – so that all efficiency differences can be attributed to the drivetrain. Despite assumed improvements in hybrid component efficiency, the efficiency advantage of the hybrid over the advanced conventional vehicle was found to shrink over time – from 30% in 1995 to 25% in 2005 to below 23% in 2015 (OTA 1995). On the other hand, assumptions about component efficiency are extremely important to these results. In the OTA analysis, for example, substituting a flywheel for the battery in the 2015 vehicle, which greatly boosts storage in/out efficiency and reduces overall vehicle weight, *increased* the hybrid-to-advanced conventional efficiency advantage to 38% (OTA 1995). In a real-world example of improvement in HEV fuel efficiency, Toyota managed to boost the performance on the EPA

[33] Maximum braking power will likely be higher than maximum motor power, since 60-0 mph braking time and distance should be expected to be substantially shorter than 0-60 mph acceleration time and distance, and acceleration uses *both* motor and engine (for parallel hybrids).

Highway cycle of its Prius HEV from about 54 mpg in 1998 to 58 mpg in 2000 with an improvement in Z60 time from about 14.5 seconds to 12.7 seconds (Hellman et al. 1998; Toyota 2000). In other words, trends in the efficiency boost afforded by hybridization will depend on the balance between improvements in hybrid designs and components and improvements in conventional drivetrains that attack the same sources of inefficiency addressed by hybridization. The net effect of these two opposing forces over time is uncertain.

## 2.6 References

Air Resources Board, 1999, *California Exhaust Emission Standards and Test Procedures for 2003 and Subsequent Model Zero-Emission Vehicles, and 2001 and Subsequent Model Hybrid Electric Vehicles, in the Passenger Car, Light-Duty Truck and Medium-Duty Vehicle Classes,* California Environmental Protection Agency, Aug. 5.

Burke, A.F., 1992, *Hybrid/Electric Vehicle Design Options and Evaluations*, SAE Technical Paper Series 920447, in *Electric and Hybrid Vehicle Technology*, SAE Report SP-915.

Cuddy, M.R., and K.B. Wipke, 1996, *Analysis of the Fuel Economy Benefit of Drivetrain Hybridization*, SAE Paper.

German, J., Honda North America, personal communication.

Hellman, K., M.R. Peralta, and G.K. Piotrowski, 1998, *Evaluation of a Toyota Prius Hybrid System (THS),* U.S. Environmental Protection Agency Report EPA-420-R-98-006, Office of Mobile Sources, Ann Arbor, Mich., Aug.

Hermance, D., 1998, unpublished material (Luncheon Keynote Presentation on Toyota Hybrid System: The World's First Mass-Produced HEV, SAE/NESEA Making Hybrid Electric Vehicles Commercially Viable TOPTEC).

Murrell, J.D., 1995, unpublished material.

Office of Technology Assessment, 1995, *Advanced Automotive Technology: Visions of a Super-Efficient Family Car*, OTA-ETI-638 (U.S. Congress, Washington, D.C., Sept.). Full report unpublished due to OTA closing.

Reuyl, J.S., and P.J. Schuurmans, 1996, NEVCOR, Inc., *Policy Implications of Hybrid-Electric Vehicles*, Final Report to NREL, Figure 11, April 22.

Schiffer, M.B., 1994, *Taking Charge; The Electric Automobile in America*, Smithsonian Institution Press, Washington and London.

Shulock, C., 2001, Air Resources Board, personal communication, Aug. 22.

Sutula, R.A., et al., 2000, *Electric and Hybrid Vehicle Energy Storage R&D Programs of the U.S. Department of Energy, 17$^{th}$ Electric Vehicle Symposium*, Montreal, Canada, Oct.

Tamor, M.A., 1996, Ford Motor Company, unpublished material.

Toyota, 2000, *Prius Product Information 2000*, brochure PR-E-00UJ03, July.

U.S. Department of Energy, 1994, *Electric and Hybrid Vehicles Program*, DOE/EE-059, April.

# Section 3
# Methodology and Modeling Issues

## 3.1 Modeling the Vehicle

This section describes the modeling of the energy use and emissions of vehicle operation. The question we are trying to address in our vehicle modeling sounds deceptively simple: What is the impact on fuel consumption, emissions, and performance of “hybridizing” a drivetrain, that is, shifting from a conventional drivetrain to a hybrid one? From a hardware standpoint, we are trying to measure the energy, emissions, and performance impact of removing the conventional drivetrain and substituting a hybrid one, that is, removing the engine/transmission/differential and substituting one of a potential variety of hybrid drivetrains (for example, an engine/generator/battery/electric motor/power split device combination), with whatever structural changes might be necessary.

### 3.1.1 ADVISOR Model and Validation

Vehicle performance (acceleration capability, gradeability, fuel use, and emissions) are estimated using the ADVISOR (Advanced Vehicle Simulator) model developed by the National Renewable Energy Laboratory (NREL) in support of the Department of Energy’s hybrid propulsion system program. ADVISOR is programmed in the MATLAB®/Simulink® environment using a modeling approach that combines backward- and forward-facing calculations.

The backward approach begins with a required speed trace that the vehicle must meet. The model first calculates the force that must be exerted at the wheels to move the vehicle as the trace requires, and checks to see whether the tires can deliver the required force without slipping. It then works backwards through the powertrain, calculating what each component must do to allow the vehicle to meet the trace, for example, the power that the engine must exert. For each calculation, the model enforces limits on what can be achieved, for example the motor/controller has speed, torque, and current limits. When the powertrain cannot achieve what is demanded, the vehicle will fall behind the trace.

For this backward approach, the model estimates the capabilities and efficiency of key components by using tables or maps of efficiency or fuel use (or emissions) versus output torque and speed (for engines and motors). These tables and maps normally are produced by steady-state testing, so they reflect conditions after warmup. ADVISOR simulates the effect of engine and catalyst warmup, as well.

In the forward-facing approach to vehicle modeling, the computational path starts with driver behavior, that is, throttle and braking behavior, calculates the effect on engine power, and continues through the transmission and the remainder of the drivetrain to compute the tractive force at the tire/road interface, which then results in an effect on vehicle movement. As in the backward-facing approach, limits on wheel slip are applied to ensure that the vehicle does not accelerate faster than the wheels' adhesion capabilities will allow. Inertia effects of the drivetrain are also accounted for.

ADVISOR acts as a purely backward-facing model as long as none of the torque or other limits of the powertrain components are exceeded by the requirements of the speed/time trace. The model is very fast in the backward-facing mode, so that multiple iterations of vehicle cases can be run quickly. In our evaluations, examination of the difference in the desired vs. the actual speed-time trace was used to determine whether a vehicle could "match the trace." All cases reported here do so; in earlier reported cases (Wang et al. 1997), one vehicle did not meet the most aggressive trace.

When the work reported here was done, few actual hybrid vehicles had been tested, and necessary details for broad sensitivity analysis of varying hybrid electric vehicle (HEV) performance capabilities, e.g., a library of engine and motor maps, were rather limited. Further, since only the Prius HEV had been thoroughly tested when this work was conducted, validation of ADVISOR against real-world hybrid vehicle performance was very limited. However, ANL and NREL tested the model in a number of ways:

- ANL has validated ADVISOR against numerous conventional vehicles for Z60 and against two Saturn SL1 models [1.9-L single overhead cam (SOHC) with manual and automatic transmission] and a VW Passat [1.9-L turbocharged direct injection (TDI) manual] for fuel economy.

- Since the model is capable of operating in a backward-facing mode and partially in a forward-facing mode, NREL has created tests in which simulated vehicles are measured using both modes. The first test asks the vehicle to meet a time/speed trace that it cannot satisfy, forcing the model into a forward-facing mode. The second test simulates the vehicle's performance on speed traces that are iteratively changed until the trace is found that is exactly the fastest that the vehicle can accelerate. For this trace, ADVISOR works strictly as a backward-facing model. ADVISOR achieved very similar results for both 0-60 mph acceleration and energy consumption in both modes (Wipke et al. 1999).

- NREL tested earlier versions of ADVISOR against industry models using identical inputs, with similar results (Wipke et al. 1999).

- Researchers at Virginia Polytechnic Institute ran ADVISOR using data from their FutureCar competition entry, a series hybrid, simulating the speed trace used by the actual vehicle and comparing actual to modeled results for fuel use and battery energy use. The ADVISOR results matched the test results within the uncertainty of the test measurements (Wipke et al. 1999).

### 3.1.2 Rules for Comparing Vehicles and Modeling Difficulties

Ideally, the hybrid vehicle/conventional vehicle pair being compared would follow a set of rules designed to make the comparison as "fair" as possible. The following rules are designed to ensure a fair assessment of the impact of shifting from a conventional drivetrain to a hybrid one:

1. Everything outside the drivetrain, with the exception of any needed structural reinforcements, will be the same. In other words, both the HEV and the conventional vehicle (CV) to which it is being compared should have the same aerodynamics, same basic structure and materials (except for reinforcements forced by the heavier hybrid drivetrain components), and the same tires (with allowances for differences in vehicle weight). This rule would be relaxed if the layout and space demanded by the hybrid drivetrain either forces negative changes or allows positive ones in vehicle size and/or aerodynamics.

2. The engines in the conventional drivetrain and hybrid drivetrain generally will be different in rated power but of the same design except for changes made possible or logical by the hybridization. Changes could range from minor design changes that take advantage of the narrower engine operating regime the hybrid design allows, to totally changing the auxiliary power unit (APU) technology, e.g., using a gas turbine in the hybrid if the hybrid operating strategy did not require the APU to follow the load.

3. The two vehicles should perform as similarly as possible, except where performance differences are inevitable because of problems too expensive to fix or advantages too attractive not to take advantage of. The primary performance indicators we used are zero to 60 mph acceleration (Z60) time and gradeability, matching within reasonable limits of accuracy the Z60 times of the two vehicles, but allowing hybrids to meet a minimum gradeability standard considerably below that achievable by the conventional vehicle. We have not at this time estimated and compared passing acceleration for the two vehicles, though this is another performance indicator that is of importance to vehicle designers.

Where these rules are not followed, it is our contention that differences in fuel consumption, emissions, and performance between a hybrid vehicle and conventional vehicle should not be attributed solely to hybridization. For example, the 1999 Japanese version of the Toyota Prius has often been compared to the 1999 U.S. Toyota Corolla, a vehicle of roughly similar size made by the same company. However, the Prius has several features different from the Corolla (low rolling resistance tires, a reduced coefficient of aerodynamic drag but larger frontal area, and variable valve control) that impact fuel economy but have nothing to do with hybridization. That is, these features could just as easily have been applied to vehicles with conventional drivetrains. Also, the Prius is significantly slower than the Corolla, with Z60 time of about 14.5 seconds; were the Corolla's gear ratios adjusted and engine size reduced to match the Prius's performance, its fuel economy would be significantly increased. The effects of these differences should be accounted for separately from the effects of hybridization. On the other hand, the effect of three additional, unique Prius features probably *should* be included as an effect of hybridization. These features are Prius's use of an Atkinson cycle in the engine,[34] its lighter engine components (the availability of boost power from the motor allows engine speed to be limited to 4,500 rpm,

[34] The Atkinson cycle, if used in a gasoline engine of a given displacement, will sharply reduce the power of the engine while increasing its efficiency. This cycle is not appropriate for a conventional drivetrain, but a hybrid can overcome its power disadvantage and thereby obtain the benefit of its higher efficiency.

yielding less stress on the engine), and its continuously variable transmission, whose unique design is made possible only by the combination of electric motor, generator, and engine.[35]

#### 3.1.2.1 Selecting a Conventional Engine/Hybrid Engine Pair for Comparison

A key problem in modeling the effects of hybridization is the difficulty of modeling a hybrid engine that represents only those features (particularly, lower power and size/weight) allowed by the hybridization. There are both philosophical and practical problems.

A philosophical problem is that reducing engine size while maintaining "all else equal," that is, maintaining the same level of technology and the same design, may not represent the best comparison between conventional and hybrid drivetrains. Instead, the degree of operating control afforded by a hybrid drivetrain may make it attractive to the vehicle designer to eliminate some engine enhancements normally used in a conventional drivetrain to maintain high engine efficiency over a wide range of operating conditions. For example, although the Toyota Prius has variable valve control and the baseline Toyota Corolla does not, it may be more likely that a hybrid designer would *remove* a costly pre-existing variable valve system in hybridizing a conventional drivetrain. This is because some hybrid engine management strategies keep the engine within fairly narrow operating limits – negating much or all of the benefits of a variable valve system, which is designed to overcome the efficiency trade-offs inherent in an engine with fixed valve timing and widely varying operating conditions. Note that a hybrid drivetrain is substantially more complex than a conventional drivetrain and the added components such as motor/controller and battery are very expensive. Thus, a primary task facing the designer of a hybrid vehicle is to remove costs wherever possible, because the vehicle will be competing with simpler, less expensive conventional vehicles.

The issue of making an "apples to apples" comparison becomes even more difficult if the hybrid engine is a gas turbine or other device that becomes practical because of the hybrid drivetrain's ability to use the battery/electric motor to follow the load, with the engine providing baseload power. For such a hybrid, it is difficult to identify an appropriate baseline engine for comparison's sake. In this report, however, we deal only with hybrids using conventional gasoline engines.

There is a practical problem with the goal of keeping all else equal. In moving from a baseline conventional drivetrain to a hybrid drivetrain with a matched (but smaller) engine, the modeler must downsize the engine without losing the basis for a valid comparison. The two most obvious downsizing methods are to scale the engine down (mathematically) or to find fuel consumption and emissions maps of a smaller engine whose design is similar enough to the original that any fuel economy and emissions differences between the two engines are primarily a function of engine size rather than design differences. An examination of the fuel economy and emissions performance of engines with essentially equivalent power but different designs reveals

[35] The inclusion of the latter as a benefit of hybridization may be controversial because continuously variable transmissions (CVTs) can be added to conventional drivetrains; however, the transmission of the Prius is both less expensive and more efficient than a "conventional" CVT would be, thus, hybridization makes this type of CVT use more likely.

that design differences can yield large differences in emissions and fuel economy. Unfortunately, there are few engine families that retain constant design over a range of displacements and power output. Consequently, modeling the hybrid's engine by selecting a conveniently-sized engine map from the library makes it difficult to distinguish which part of any energy and emissions differences between the conventional and hybrid vehicles are due to hybridizing the drivetrain and which are due to differences in engine design.

Another approach to modeling a reduction in power is to reduce peak rpm (modeled by deleting the engine map above the selected peak rpm), as done in the Prius. However, it appears more likely that, in the long term, automakers will place physically smaller engines in their hybrids, and obtain them by redesigning off-the-shelf engines, designing new engines, or purchasing smaller engines from suppliers. We could model reduced displacement by assuming a reduction in the number of cylinders, but there would be changes in noise, vibration, and harshness (NVH) in an engine downsized in this manner, and this would still provide limited size options. Finally, we could model a downsized engine by reducing the peak torque line and associated isobars of a baseline engine by a constant. This option is attractive because it offers an infinite number of power levels. However, the approach ignores the real-world discontinuities that arise when cylinders are reduced in size, which is the physical analog of this approach.

We have chosen the scaling approach of reducing the peak torque line and associated isobars of the baseline CV engine by a constant to achieve the map of a downsized engine of the same technology. We note, however, that this approach automatically introduces errors into the modeling process.

In this study, we seek to project the effect of hybridization in the future, given the likelihood that large numbers of hybrid vehicles will not enter the U.S. market until 2005 or later. Some components of hybrid and conventional drivetrains are changing at a faster pace than others, partly because they are at different stages of development and partly because there are different levels of resources being expended toward their improvement. Consequently, current state-of-the-art data may not reflect likely future increases in component efficiencies, complicating the modeling process. Although higher future efficiencies can be assumed in the modeling process, it is not possible to recreate the effects of the unknown design and materials changes that will likely accompany the increase.

Finally, although this analysis attempts to compare conventional and hybrid vehicles that are close to equivalent in performance, in practice the two will not have identical performance characteristics, and in some cases differences may be large. In particular, using our design rules, an HEV's gradeability will be inferior to the "performance equivalent" CV's grade-climbing ability. Also, grid-connected hybrids expected to operate part-time as EVs may have substantially different performance from CVs. For example, in the cases we examined, the hybrid's acceleration capability in EV mode was inferior to the CV, although the development of higher-specific-power batteries may eventually allow equivalent performance; in HEV mode, for the parallel designs, the HEV's acceleration was somewhat superior to the CV. Some HEV designs with limited battery energy storage may occasionally encounter driving situations in which the batteries have been discharged and only engine power is available, reducing performance capability temporarily. The Toyota Prius has a warning light to alert drivers to low battery charge and reduced performance. In other words, readers of this and other analyses of HEV capability should be aware of the potential for some "apples to oranges" comparisons where side-by-side comparisons are between vehicles whose performance capability is not completely equivalent. Further, the drivetrain changes may make the performance of hybrids very sensitive to design details, including control strategies, with subsequent uncertainty in predicting what performance actually will be. For example, the Z60 time of a hybrid will depend strongly on whether the control strategy allows the engine to be left on when the vehicle is stopped (which would, however, increase fuel use) or, when the vehicle is electrically launched, whether the engine will be turned on at low vehicle speeds when high power is demanded. If the engine is turned off when the vehicle is stopped, acceleration time will also depend on the delay between the power demand signal (depressed accelerator) and engine start and attainment of full power. The potential for vehicle-to-vehicle variation in these factors further complicates the attainment of fair comparisons between vehicles.

The following discussions lay out more of the modeling difficulties we encountered.

#### 3.1.2.2 Engine Maps

Engine maps are representations of an engine's fuel consumption or emissions characteristics in which brake-specific fuel consumption or emissions are plotted as a function of rpm on the x axis and torque [or brake mean effective pressure (BMEP)] on the y axis. What appears on the fuel consumption map are iso-bsfc lines, that is, lines of constant brake-specific fuel consumption; the maps look similar to topographic maps showing lines of constant elevation. Similarly, the emission maps have iso-emissions lines with the same x and y axes. For conventional vehicles, ADVISOR and other second-by-second vehicle simulation models combine these maps with a transmission model (which determines where on the map the engine will be operating for a given demand for power) and, for emissions calculations, a catalyst model to estimate the instantaneous fuel consumption and emissions of the vehicle. For hybrids, maps of electric motors, controllers, batteries, and/or generators are also necessary.

Having accurate engine maps is crucial to obtaining credible fuel consumption and emissions estimates for hybrids and conventional vehicles, but obtaining adequate maps is far from simple. Aside from the problem of scaling discussed above (Section 3.2.2.1), we encountered the following problems:

1. **Availability of emissions maps.** A reasonable number of fuel consumption maps for engines of various sizes and technology levels are available in the scientific literature or informational literature prepared by engine and vehicle manufacturers. There are very few maps of emissions available, however. We did have access to maps and data from the Federal Test Procedure Revision Project (FTPRP) and the National Cooperative Highway Research Program (NCHRP). These projects measured second-by-second emissions and fuel consumption as the vehicles followed prescribed driving cycles. This project stretched the measurement state-of-the-art, particularly with regard to equipment response times and dealing with lags between engine changes and tailpipe emission responses. Perhaps as a result of these issues, we found that our estimates of fuel consumption using FTPRP and NCHRP data disagreed with published engine map

information for the same engines by a few percent, generally giving optimistic results. Presumably, there are similar problems with the emissions maps, although we did not have the same opportunities to compare these with manufacturers' data. Despite these problems, however, we had no other source of emissions data, and our emissions maps were derived directly from the FTPRP and NCHRP emissions data.

2. **Gaps in the available fuel consumption maps.** Given the measurement difficulties noted above with FTPRP and NCHRP fuel consumption data, we chose to use manufacturers' fuel consumption maps as the baseline for use in ADVISOR. However, these maps provided accurate information only for positive load conditions, and then only for moderate and higher load levels. Much of the time, however, engines operate at low or even negative load, i.e., at idle and during braking or coasting (negative load implies "engine braking" is occurring). Although the *rate* of fuel consumption at idle or during braking or coasting is low, the *time* a conventional vehicle spends at these conditions is so high during most cycles that the *fuel consumed* during these conditions is important (e.g., between 15 and 20% of total fuel consumed during the EPA FTP cycle). Because a large portion of a hybrid's fuel economy advantage over a conventional vehicle is due to the way it handles engine operations during low and negative load (it turns the engine off or maintains engine output at an efficient level, using any excess output to recharge the battery), accurately measuring energy use for both CVs and hybrids during these periods is important to accurately gauging hybrids' fuel economy advantage. For this reason, we used FTPRP and NCHRP fuel consumption data to fill in the low and negative load areas on the published maps. Note that CVs use fuel during these conditions, whereas hybrids often do not (their engines usually are turned off).

3. **No accounting for engine transient effects.** The published fuel consumption maps we used are constructed by running the engine at constant speed and load, measuring fuel consumption rates, and then repeating the measurements over the desired range of speed and load. Thus, the maps measure steady-state fuel consumption and provide no information on effects of engine transients in operations such as acceleration and deceleration. This may be important to the modeled comparisons of hybrids and conventional vehicles because some hybrid designs moderate or eliminate most engine transients. On the other hand, accurate fuel economy results are obtainable for CVs without accounting for engine transients, since validated simulations of conventional vehicles have used the same type of steady-state engine maps that are used here for simulating hybrid vehicles. At this time, we are not able to estimate the magnitude of the effect of not accounting for engine transients.

4. **Difficulty of modeling emissions.** Emissions rates for hydrocarbons and carbon monoxide can vary by thousands of percentage points as engine and catalyst conditions change, demanding a level of precision in tracking these conditions that is difficult to obtain in modeling. For example:

    - Using a "one size fits all" transmission model means that, however accurate the emissions map, potentially large errors can be introduced by differences between the rpm/torque points selected by the model and the actual points that would have been selected by the physical transmission.

- Emissions control state of the art changes quite rapidly, so available data are often “behind the curve.”

- Tailpipe emissions are a function of both engine out emissions and catalyst efficiency; the latter is highly sensitive to temperature variations, variations from stoichiometric exhaust conditions that may occur during deceleration, and other conditions that are hard to predict and are likely to vary with changes in manufacturer design strategy.

- Runs of ADVISOR predicted that a small emissions “spike” occurs at hot or warm restart of the engine. Some limited experimentation on a single engine/control system combination found that such spikes were small for the time between engine starts typical of hybrid operation. Control strategies for hybrids often demand that the engine be turned off and on several times during a driving cycle, yielding multiple hot or warm restarts. Thus, further experiments to ensure accurate prediction of restart emissions may be important in modeling hybrid emissions. However, the nature of the emissions reaction to restarts will depend on the behavior of the catalyst and the precise details of the engine and emissions control strategy and hardware (aside from the catalyst, monitors and computer controls may also be important). These details are not likely to be known for new or hypothetical hybrid vehicles; control system data are far more proprietary than engine maps. We do note that the 1999 Prius hybrid is as clean as many clean gasoline vehicles, so the aforementioned spikes do not appear to be a problem for this vehicle (Santini et al. 1999).

We concluded that the emissions estimates produced by our ADVISOR runs probably were an order of magnitude less reliable than the fuel consumption estimates. We have decided in this report to present only the fuel economy results until the reliability of the emissions estimates made with ADVISOR has at least been verified by ongoing second-by-second emissions testing at ANL.

#### 3.1.2.3 Adequacy of Transmission Modeling

At every moment of the driving cycle, the transmission determines the operating point of the engine, that is, the combination of BMEP and rpm that will produce the required load. This means that an accurate transmission model is needed to provide accurate estimates of both fuel consumption and emissions, since these are functions of where on the fuel consumption and emissions maps the engine is operating.

To test the validity of ADVISOR’s transmission model, we compared “data clouds” (plotted second-by-second data points that show where the engine is operating across the entire driving cycle) for vehicle dynamometer tests from the Federal Test Procedure Revision Program (FTPRP) and for modeled results from ADVISOR. We discovered that the original version of

ADVISOR's 5-speed transmission model tended to put the modeled engine into a portion of the maps where real engines do not operate. Figure 3-1 shows a fuel consumption map for the Saturn 1.9-L SOHC engine, with the shaded area illustrating those portions of the map where the FTPRP-tested engine operated. The ADVISOR-modeled engine often operated in region C on the map, a lower efficiency region outside the shaded area, on the same driving cycle tested in the FTPRP. The differences between the actual tested engine and the ADVISOR-modeled engine apparently occurred because the ADVISOR transmission model emphasized increases in engine rpm to obtain higher power, whereas a real conventional vehicle transmission emphasizes increases in torque to obtain more power. In other words, where a real transmission would increase power by pushing the engine operating point up in the figure, the early ADVISOR transmission simulation pushed the operating point to the right, into region C.[36]

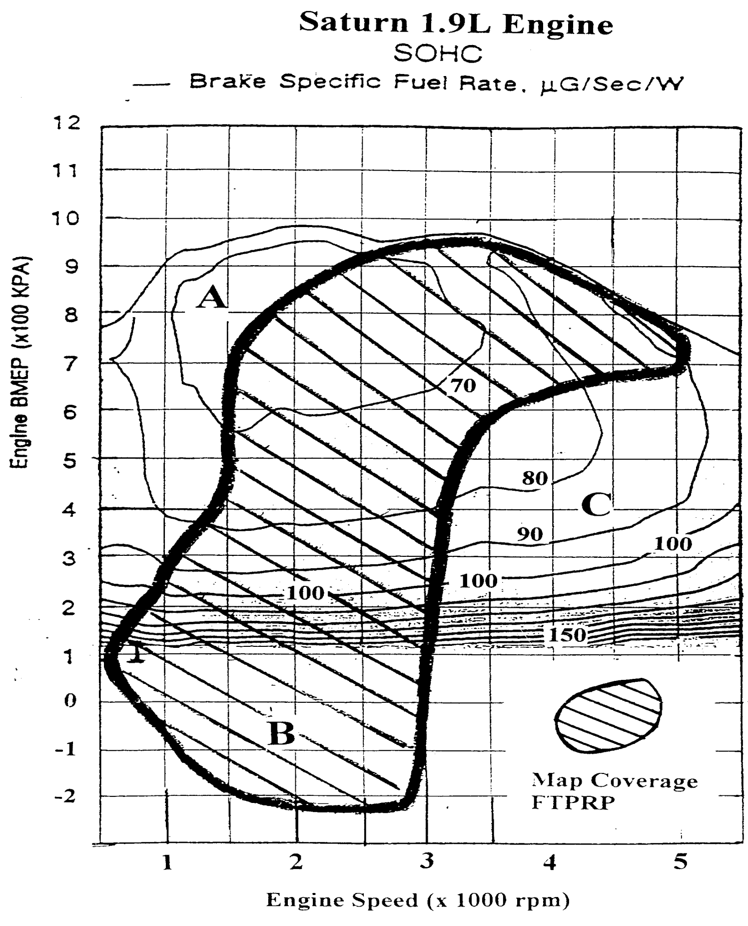



**Figure 3-1 Saturn 1.9-L Fuel Use Map with FTPRP Coverage**

---

36 Region A is an area of the map that empirical information implied cannot be reached by a conventional transmission. The Toyota Prius, with a unique continuously variable transmission, can reach region A. Region B represents deceleration. Point I represents idle.

After the Hybrid Electric Vehicle Technology Assessment (HEVTA) project developed this evidence and developed a basis for appropriate changes to the model, NREL, ADVISOR's developer, incorporated recommended revisions to the shift logic of the transmission model in ADVISOR. The revised transmission model now reasonably reproduces a real transmission's behavior in a conventional vehicle. This project also provided funding for development of the automatic transmission model added to ADVISOR. The transmission model was developed by Dill Murrell.

#### 3.1.2.4 Zero to 60 mph Acceleration Times

Zero to 60 mph acceleration time represents a key factor both in defining vehicle performance, to ensure that vehicle-to-vehicle comparisons are truly between equivalent vehicles, and in sizing the powertrain correctly.[37] Consequently, it is extremely important to be able to consistently and accurately translate powertrain (and other vehicle) characteristics into Z60 times and vice versa.

We encountered significant problems with measuring and estimating Z60 time. First, there appears to be no industry standard for physically measuring Z60 time, so that different testing organizations consistently obtain different Z60 values for identical vehicles. The differences are particularly stark for manual transmission cars, which is not surprising since the degrees of freedom afforded the drivers are that much greater than with an automatic transmission. Second, estimating Z60 time requires a complex calculation with several judgment inputs, so that estimated Z60 time values appearing in the literature should not be used without understanding the underlying test protocols. Two vehicles of apparently identical performance, as indicated by estimated Z60 times obtained under different test protocols from different sources, would probably perform quite differently if tested in the field.

**Z60 measurements.** We examined Z60 test times from *Consumer Reports, Car and Driver,* and Daniel Heraud's "Carpoint" website, and found significant differences among the three sources. The largest differences were between manual transmission cars tested by *Consumer Reports* and *Car and Driver*, with *Consumer Reports'* test times about 17% slower than *Car and Driver's*. For higher performance cars with Z60 times of about 6 seconds, *Car and Driver's* tests brought the cars to 60 mph about 1 second faster than *Consumer Reports'*. The gap widened to about 2 seconds for Z60 times approaching 12 seconds.[38]

[37] With regard to powertrain sizing, Argonne's baseline method has been first to size the engine to achieve vehicle minimum continuous gradeability requirements of 6.5% grade @ 55 mph for 20 minutes, and then to size the battery and electric motor to achieve the Z60 time goal (8, 10, or 12 seconds).

[38] These values reflect plotted statistical fits of recent (1994-1998) values of Z60 time versus inertia weight/peak power rather than compared tests of identical vehicles, but the results resemble an earlier examination of test results from *Consumer Reports* and enthusiast magazines for identical vehicles (Santini and Anderson 1993).

A comparison of test results for automatic transmission-equipped cars between *Consumer Reports* and the Heraud website show considerably smaller differences, which is not surprising given the fewer degrees of freedom available with an automatic transmission.

There are limited performance tests for hybrids available. EPA conducted Z60 tests on the Japanese version of the Prius during extensive testing for fuel economy and emissions performance (Hellman et al. 1998). EPA found that the Japanese Prius's Z60 times varied significantly with the state-of-charge of the battery. With the battery fully charged, this Prius's Z60 time was about 14 seconds. After deliberately discharging the battery by coasting down rather than braking, thus avoiding regenerative braking, the Z60 times increased gradually to about 20 seconds or so, with the 20-second Z60 probably about the acceleration capability of the engine alone, without motor assist.

*Car and Driver* conducted similar tests of the Japanese Prius, at full and zero battery state of charge (SOC). More recently, *Consumer Reports* and Toyota have published Z60 test results for the U.S. version, presumably at full SOC. Finally, both *Car and Driver* and *Consumer Reports* have tested the Insight, with *Car and Driver* testing it at varying states of charge.

Figure 3-2 plots the Z60 times for both conventional and hybrid vehicles from *Consumer Reports*, Heraud (conventional only), and *Car and Driver* as a function of the vehicle power-to-weight ratio, and adds a standard EPA equation of the relationship (for conventional drivetrains) for comparison's sake. The figure also shows some results from ADVISOR runs, for conventional vehicles. These tests confirmed that ADVISOR predicted slower acceleration with automatic transmissions than with manual transmissions, though the difference may not be quite as great as in *Consumer Reports'* tests.

**Modeling Z60 time.** We also discovered that alternative models (and methods) we had been using to estimate Z60 time for identical vehicles gave different estimates. We had been using two models, ADVISOR and Hybrid Electric Vehicle Component Sizing and Vehicle Cost model (HEVCOST), to estimate either Z60 time given vehicle characteristics, or drivetrain component power given required Z60 time (and gradeability). Our initial versions of HEVCOST and ADVISOR were close in predictions of Z60 times for series HEVs (within ~ 0.5 second difference) but were far apart in Z60 predictions for conventional vehicles and parallel hybrids – with HEVCOST predicting significantly faster Z60 times (or lower power requirements to obtain the same Z60 time). The differences in results led to careful reexamination of both approaches. After these evaluations, we made changes to both models, bringing them closer together in their

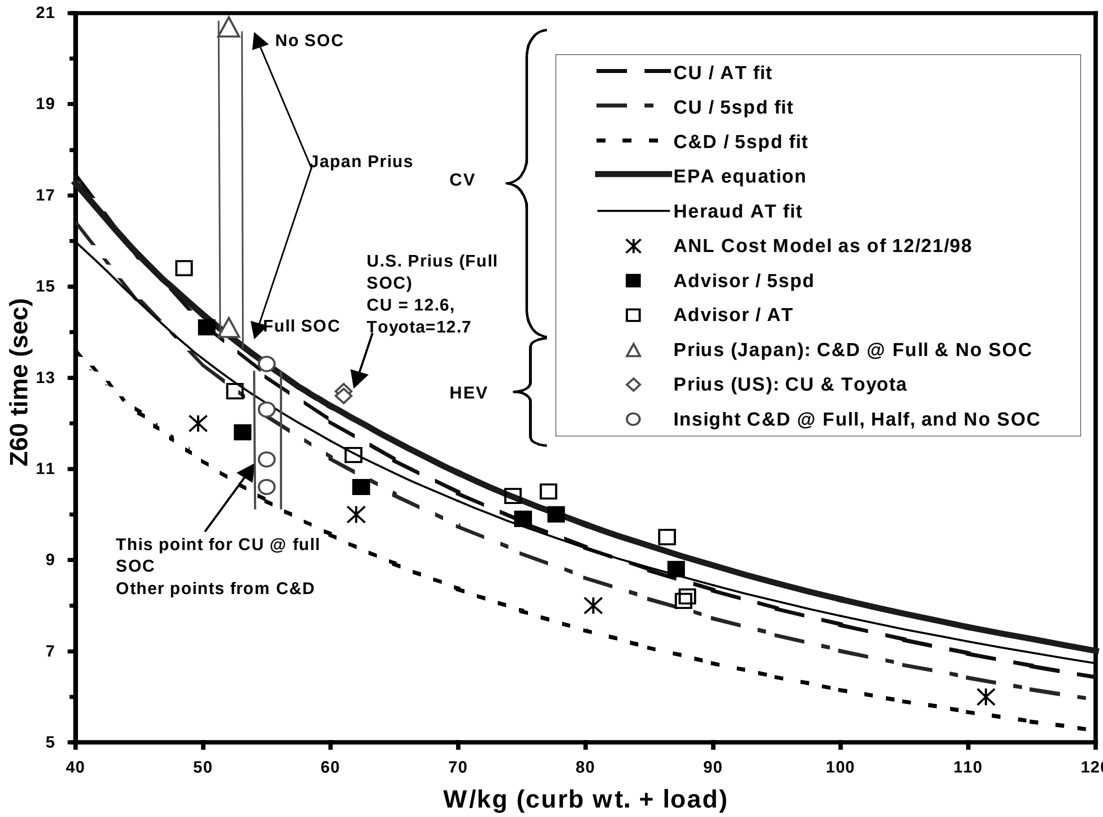



**Figure 3-2 Plots of Measured and Estimated Z60 Time vs. the Vehicle Power-to-Weight Ratio (watts per kilogram, curb weight plus load) for Conventional Vehicles and Hybrids**

estimates, and better matching them to measured Z60 times. Some of the obvious areas of concern in estimating Z60 time are:

- For hybrids, is the engine on or off at start? The need to turn the engine on will cause a delay in reaching full power, although the electric motor can launch the vehicle (at lower acceleration) even with the engine off. ADVISOR assumed the engine was on in series HEV calculations, but off in parallel HEV calculations; in its original version, HEVCOST assumed the engine is on for both types of hybrids. In all likelihood, hybrids will be designed to turn the engine off at stop, at least for a default mode, to conserve fuel.[39] However, hybrid designs may allow drivers to override the engine off feature. This raises the question of whether announced Z60 times will reflect normal (engine off at stop) driving conditions or competitive (engine on) conditions. Further, if the engine is on, different testing organizations testing a manual transmission HEV may use a different starting rpm. We suspect that *Consumer Reports* starts its tests at idle and *Car and Driver* starts at higher rpm. The relative positions of the best *Car and Driver* test of

[39] However, for effective emissions control, after first start-up the engine probably will not turn off until the catalyst reaches lightoff temperature; the Prius engine behaves this way.

the Insight, and the single *Consumer Reports* test of the Insight (Figure 3-2) are consistent with this expectation.

- For manual transmission cars, how long are the transmission shift delays? This is a function of driver and transmission capability. Vehicle simulation models are likely to have a single transmission model for all vehicles. The ADVISOR model does allow the analyst to specify shifting delay, gear ratios, final drive ratio, and torque converter characteristics; any good model should do so.

- Does the model consider wheel slip? For full power acceleration, wheel slip can add significantly to Z60 times, since tire/pavement adhesion limits affect the amount of power that can be used for acceleration. Note that the type and size tires used are a critical determining factor. As part of our model verification and calibration process, we modified the wheel slip submodel in ADVISOR, increasing the adhesion limits and reducing achievable Z60 times.

- Are the transmission shift points always at the redline? Note that a typical Z60 test will have one or two upshifts, with the second upshift often occurring quite close to 60 mph (so that small differences in the shift point can place the second shift inside or outside of the Z60 test); the difference in delay time between one or two shifts is not insignificant. In an actual test run, an aggressive tester might avoid the second shift by leaving the transmission in second gear and briefly exceeding the redline.

- Is engine inertia accounted for? At startup (unless the test driver races the engine in neutral) and after each shift, there is a small delay for the engine to reach the high rpm required for maximum power. We added an inertial component to our early version of ADVISOR to improve the accuracy of its Z60 calculation; the effect was to increase slightly estimated Z60 times.

#### 3.1.2.5 Hybrid Design and the Impact of Cost Considerations

Our modeled comparisons of equivalent conventional and hybrid vehicles have the disadvantage that the hybrid vehicle's design is based on a simplistic set of performance targets and design rules rather than the sophisticated design process that would actually occur in developing a commercial vehicle (for example, accounting for cost and a range of performance requirements including start-up acceleration, passing acceleration, top speed, shift feel, etc). In this study, the base vehicles are designed to meet simple Z60 and 55 mph gradeability targets, with the sizing of drivetrain components generally obeying simple rules: engine sized to meet the gradeability target; battery and motor sized to provide the additional power needed to meet the acceleration target. These rules yield a vehicle that superficially performs in a manner similar to a conventional vehicle and whose overall performance is likely to be acceptable to most users. However, the modeled vehicle design lacks two important considerations:

1. The fuel economy and emissions outputs have not been used to redesign the vehicle in an iterative fashion. It is quite possible that other design rules could produce a more

efficient and/or lower emitting vehicle that still performed adequately or, alternatively, that strategies to hold emissions or fuel consumption down could diminish performance.

2. Cost estimates were similarly not used in the initial set of model runs to redesign the vehicle. Thus, following the design rules, acceleration performance improvements were obtained primarily by increasing battery and electric motor power capacity, even though increasing engine power probably would be cheaper at U.S. fuel prices. The selected approach does result, however, in better fuel economy.

The HEVTA has conducted some sensitivity analysis to allow for the second consideration, e.g., allowing engine power to exceed gradeability requirements (with reduced motor and battery power requirements) to produce a less expensive vehicle. However, in general it must be remembered that the hybrid designs studied to date are likely to be significantly different from eventual commercial designs.

#### 3.1.2.6 Fair Treatment of Time and Context

A fair treatment of the hybrid/conventional comparison will ensure that assumptions about technological progress and context will apply to both drivetrains. Thus, if the hybrid is assumed to be equipped with an advanced, efficient battery and electric motor that might not be available until 2005, comparing it to a 1999 conventional vehicle introduces a bias against the CV. It would be fairer to the comparison to assume improvements to the conventional drivetrain that could be expected to be made by 2005, although this clearly introduces additional uncertainties. The likely result would be that the relative fuel-economy advantage of the hybrid will shrink, because advanced engines and transmissions will reduce some of the same losses that are targeted by hybridization.

A more subtle issue is context: if the hybrid is commercially feasible despite its higher cost, this probably means that, in the scenario being modeled, fuel economy is valued highly. This might mean, for example, that turning the (conventional) engine off during zero road load situations (braking, coasting, standing) would be acceptable to consumers. Turning the engine off during stops, braking, and coasting is a typical strategy for a hybrid and a significant source of its fuel savings; if the conventional drivetrain could use the same strategy, this would narrow the fuel consumption gap between the two. But if the design for idle-off involved replacing the starter and alternator with an integrated motor/generator and using a larger battery, this might stretch the traditional meaning of “conventional drivetrain.” Such a design could also be considered an extreme example – the mildest of mild hybrids.

#### 3.1.2.7 Calculating the Energy Use of Grid-Connected Hybrids

Computing the energy use of grid-connected HEVs is complicated by their dual mode of operation and potential for recharge from the electrical grid. For grid-independent HEVs, computing energy use is simply a matter of modeling fuel use over selected driving cycles and reporting vehicle fuel use either separately for each cycle or for a time period consisting of several cycles of different types, strung together. Either way, this is a straightforward exercise, with all energy supplied by a single fuel stored onboard. That computing the energy use of a grid-connected hybrid is *not* straightforward can be demonstrated by following the course of a day's travel (Figure 3-3):

- We can assume that the vehicle begins the day as an electric vehicle (EV), with the battery fully charged (e.g., at 0.95 SOC) and the engine not operating. This may not always be the case, since vehicle operators might want to "save" the vehicle's EV range for later in the trip (or day) when the vehicle might have to operate in an urban area open only to zero emission vehicles. Some European cities have established "zero emission zones," and conceivably some American cities might do the same. However, where ozone reduction is the primary focus, reducing early morning emissions – requiring initial use of the vehicle in zero emissions mode – seems most likely.

- Assuming an EV range R, if the vehicle's total travel is less than R miles, the vehicle will operate all day on battery power and end the day at a battery SOC greater or equal to the minimum allowed (e.g., 0.2 SOC, which is the value we have assumed in our analysis). If the vehicle is recharged at night, all of that day's miles (≤ R) may be said to have been powered from the grid.

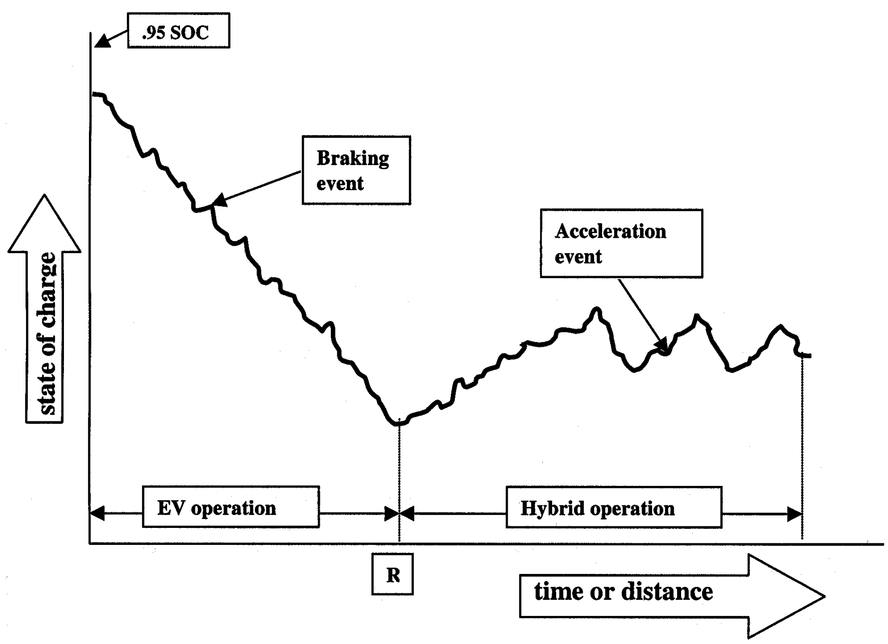



**Figure 3-3 A Day's Driving for a Grid-Connected Hybrid Vehicle: SOC vs. Time or Distance**

- If the vehicle's travel on that day is greater than R, after R miles the engine will turn on and the vehicle will operate in hybrid mode. For a time after the engine starts, the engine will work to recharge the battery until it reaches a predetermined state-of-charge range selected to allow both long battery life and high potential for grid recharging.[40] After this range is reached, the vehicle's control system will seek to keep the battery SOC within this (narrow) operating range, to extend battery life. When the battery is recharged overnight, the grid can provide only that electricity needed to raise the battery's charge from the SOC when the vehicle was turned off (either somewhere between 0.2 and the bottom of the operating range if the vehicle is turned off before the operating range is reached, or somewhere within the operating range if the vehicle is turned off later) to the fully charged state. On these days, the grid will have provided the energy to power some number of miles less than R, with the rest powered by the vehicle's onboard fuel.

Uncertainty about the SOC range likely to be chosen for normal HEV operations introduces difficulty in estimating the amount of grid electricity that a grid-connected hybrid can use. As noted above, on trips that significantly exceed the hybrid's EV range, the amount of recharging will depend on the difference between the SOC at the end of the trip (somewhere in the SOC operating range) and the maximum SOC, say 0.95. The lower the SOC operating charge range, the more potential there is in the battery for recharging. Thus, the choice of operating range is likely to be a trade-off between maximizing battery longevity, which might require a fairly high SOC range (e.g., 0.5-0.6[41]), and maximizing the amount of grid electricity used, which would require a low range (e.g., 0.2-0.3). At this time, we do not know enough about the quantitative effect on battery longevity of different operating SOC ranges to provide a reliable assumption about the range likely to be chosen by manufacturers. It is our understanding, however, that a wide swing in SOC from almost fully charged (0.95) to almost fully depleted (0.2) will have a highly detrimental effect on battery life compared to a modest 0.5-0.6 swing.

Individual driving characteristics of grid-connected hybrids present another uncertainty about their energy use. A simple example will illustrate the dilemma. If a grid-connected HEV were to travel 10,000 miles per year, it would average about 27 miles per day. If its EV range were 30 miles and its travel extremely regular, for example, if it were a mail delivery vehicle with a 27-mile daily route, or primarily a commuting vehicle with a 27-mile round trip, it might rarely be forced out of its EV mode and could "fuel" most of its miles from the grid. On the other hand, if its travel were highly irregular, with a mix of "short travel" days (during which it was idle or traveled only a few miles) and days when it was used intensively, with daily distances well beyond its EV range, half or more of its travel could be fueled by its onboard fuel stores.

---

[40] Maximizing grid recharge means selecting as low an SOC operating range as possible (but still avoiding SOCs below the point where specific power experiences sharp declines, about 0.2 SOC in the NiMH batteries that we simulated), e.g., 0.2-0.3 SOC. Maximizing battery life *may* imply a higher SOC operating range, but we are not aware of data on the interplay of battery life and operating range.

[41] The Prius HEV uses an SOC range in this vicinity. ANL tests show that battery SOC stays within a range of 0.55 and 0.60 on the Japanese 10.15 cycle (personal communication, Aymeric Rousseau, Argonne National Laboratory).

Consequently, understanding the usage patterns of grid-connected HEVs will be crucial to estimating the nature of their energy use.

In other words, a grid-connected HEV will use both grid electricity and fuel to power its miles, with the split between the two determined in large part by the type of driving being done, the vehicle's electric range, and the operating SOC range. A vehicle that travels short distances daily might obtain all its energy from the grid; one that travels long distances might obtain considerably less than half its energy from the grid.

HEV energy use can be modeled from the "daily miles traveled" data available from the Nationwide Personal Transportation Survey (FHWA 1997). Figure 3-4 (cumulative share of vehicles traveling vs. total miles traveled daily) shows that, on an average day, about 40% of vehicles driven travel less than 20 miles.[42] We might assume that HEVs conform to the daily travel distance distribution reported by the survey. However, using this data implicitly assumes that the travel patterns of grid-connected HEVs will be identical to the patterns of all vehicles, and this seems unlikely. Grid-connected HEVs will be more expensive than both CVs and grid-independent HEVs in initial costs and, at U.S. gasoline and electricity prices, probably in life cycle costs as well, and their performance is somewhat limited in EV mode. They are likely to be purchased by individuals who either require, or value highly, their EV capability, and these will not be average drivers. Although we can, and will, speculate about their tripmaking characteristics,[43] computing electricity and fuel use involves adding another uncertainty to the already large number of uncertainties present in our other calculations of HEV energy use.

Assuming that the full range R can be recharged electrically when the day's travel distance exceeds R (that is, ignoring the previously discussed loss of rechargeable distance that occurs after the HEV mode commences), HEVs with a 20-mile EV range could recharge 40% of all miles traveled electrically (this potential was first recognized by Reuyl and Schuurmans 1996). This percentage of recharge may be reduced substantially when engine-induced recharge is considered, with the amount depending on the minimum SOC and the HEV operating SOC range. In all likelihood, our accounting for engine recharge (assuming a 0.5-0.6 SOC operating range) would reduce the 20-mile HEV to about 25-30% electrification. If battery longevity can be maintained with a very low operating SOC range, then this percentage would move upwards toward 40%.

---

[42] Note that the graph represents only a snapshot of what happens on an average day, and on a different day, it is quite possible that a different group of vehicles will be traveling less than 20 miles. In other words, the graph does *not* mean that 40% of vehicles travel less than 20 miles per day as an annual average (that is, 6,300 miles/year); it is more likely that far fewer vehicles travel this little over the course of a year. Strictly speaking, the graph means only that the average driver drives less than 20 miles about 4 days out of every 10 that he or she drives.

[43] We would guess that purchasers of grid-connected hybrid vehicles would spend more-than-average time in congested urban driving conditions (where HEVs achieve maximum benefit/mile) or at least in non-highway conditions, drive more miles than most such drivers, and regularly return to a location where the vehicle can be recharged.

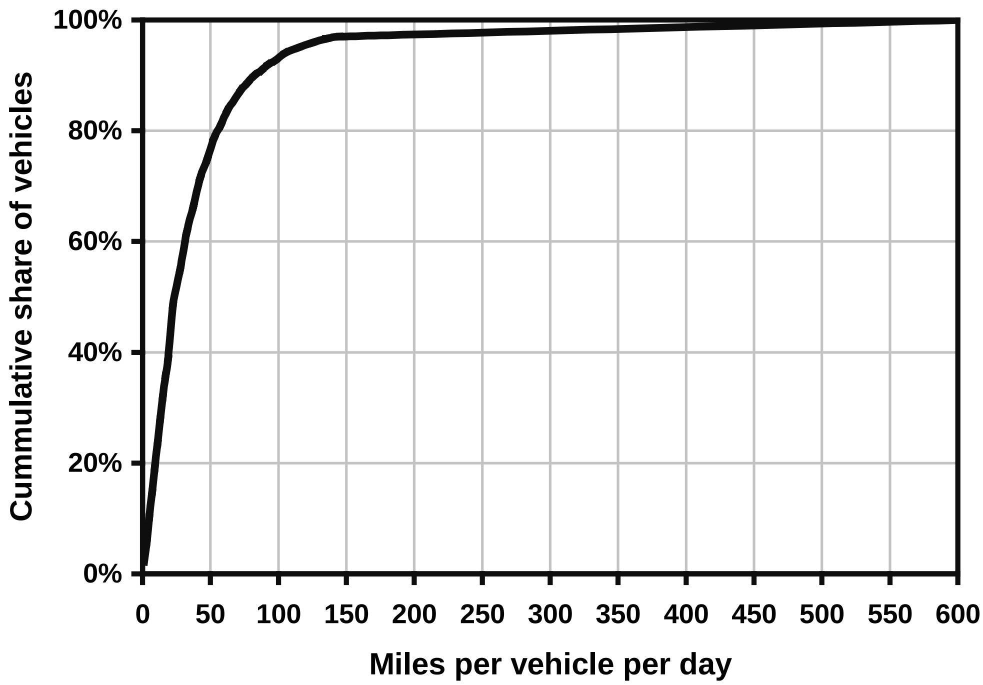



**Figure 3-4 Cumulative Share of Vehicles Traveling vs. Miles Traveled, from the Nationwide Personal Transportation Survey**

## 3.2 Cost Modeling

The Hybrid Electric Vehicle Component Sizing and Vehicle Cost model, HEVCOST, is a direct extension of the conventional and electric vehicles manufacturing and retailing cost analysis described by Cuenca, Gaines, and Vyas (2000) and Vyas et al. (1998). A few aspects were adapted for hybrid electric vehicles (HEVs). The analysis relies on first identifying those vehicle components that would be common between a CV and a hybrid electric vehicle, and then estimating the CV retail price share of these common components. The analysis then develops a separate estimate of the cost of those components unique to the HEV – primarily the powertrain. Using a relationship between vehicle component manufacturing cost and retail price developed by the study team, the retail price of the HEV components (mostly the powertrain) are determined and added to the price of the shared components to yield total vehicle price.

Argonne developed a separate procedure (described in Appendix C) for estimating powertrain component power requirements and mass, and cost equations were derived for the powertrain components as a function of the component power ratings. The resulting estimates serve as a useful initial value for the ADVISOR model, which then iterates to a more exact set.

The cost estimation procedure is designed to be applied to high-volume production of hybrid electric vehicles. It assumes that the body and chassis components of a hybrid electric vehicle will be very similar to a conventional vehicle and will be mass-produced by an original equipment manufacturer (OEM).

### 3.2.1 Common Components' Retail Price Equivalent

The cost analysis separates the conventional vehicle into four groups: (1) body, (2) engine, (3) transmission, and (4) chassis. The retail price contributed to electric vehicles by each group was determined by Cuenca, Gaines, and Vyas (2000), who also classified each component or group of components as fully common, partially common, or not common between conventional and electric vehicles. Subsequently, that analysis was extended to apply to hybrid electric vehicles and is reported in Table 3-1.

With the exception of the instrument panel and the heating, ventilating, and air-conditioning (HVAC) system, the body group is expected to remain practically the same between a CV and an HEV. The HEV instrument panel will have specific displays for new components and HEV operation. Its HVAC system ducts and blowers will be very similar to those of a CV, but the system would be powered and configured differently. Although the initial HEVs are expected to have an internal combustion engine (ICE) power plant, the entire engine group is identified as "not common" because proposed HEV engine systems are different from those used in the CVs. Aside from having lower power ratings than their CV counterparts, HEV engines are not likely to have a separate alternator and a starter. They may have one alternator/starter or they may use, when one is available, a generator for starting the engine. HEV engines may operate within a narrower range of speeds than a CV engine and may use combustion cycles, such as the Atkinson cycle used by the Toyota Prius, that a CV engine would not.

The transmission group, too, is marked "not common." The parallel HEV's transmission must coordinate two power sources, an ICE and an electric motor. Several novel approaches are being developed for this configuration, much different from the present CV transmissions. In the series configuration, the motor could be connected to a simple gear drive to transmit its power, although some applications might require a two-speed transmission. In either configuration, a separate cost estimate is required. Within the chassis group, several subgroups are marked "partially common." The exhaust system, fuel storage, and fluids subgroups are likely to be smaller and perhaps different from the CV's systems. The steering and brake subgroups may differ in their power source and design. The chassis electric system may use a different power source and voltage, depending upon the OEM design choices.

The analysis discussed in this report assigns shares of retail price to each group of the CV components for a midsize car – a four-door sedan with a four-cylinder engine, automatic transmission, and air-conditioning (HEVCOST also can evaluate minivan and subcompact vehicles). Table 3-2 provides a summary of the allocation by major groups.

**Table 3-1 Common and Dissimilar Components of CV and HEV**

| CV Groups and Subgroups | Fully Common | Partially Common | Not Common |
|---|---|---|---|
| **Body Group** | | | |
| Body-in-white | X | | |
| Paint and Coatings | X | | |
| Glass | X | | |
| Interior Body Trim | X | | |
| Exterior Body Trim | X | | |
| Seats | X | | |
| Instrument Panel | | X | |
| Restraint System | X | | |
| Body Electrical Components | X | | |
| Heating, Ventilating, Air-Conditioning (HVAC) | | X | |
| **Engine Group**[a] | | | |
| Base Engine | | | X |
| Emissions Control | | | X |
| Engine Accessories | | | X |
| Engine Electrical Components | | | X |
| Cooling System | | | X |
| **Transmission Group**[b] | | | |
| Transaxle | | | X |
| Clutch and Actuator | | | X |
| Transmission Controls | | | X |
| **Chassis Group** | | | |
| Frame | X | | |
| Suspension | X | | |
| Steering | | X | |
| Brakes | | X | |
| Exhaust System | | X | |
| Fuel Storage | | X | |
| Final Drive | X | | |
| Wheels and Tires | X | | |
| Bumpers, Fenders, and Shields | X | | |
| Chassis Electrical Components | | X | |
| Accessories and Tools | X | | |
| Fluids | | X | |

[a] Although the HEV has an engine, the entire engine group will be designed differently. Hence it is treated as “not common.”

[b] An HEV transmission could range from a continuously variable transmission to a set of reduction gears.

**Table 3-2  Allocation of MSRP to Midsize Car Groups and Common Components**

| Vehicle Group | CV Price Share (%) | Share Common to HEV (%) |
|---|---|---|
| Body group | 28.46 | 28.46 |
| Engine group | 21.53 | 0.00 |
| Transmission group | 5.03 | 0.00 |
| Chassis group | 23.94 | 22.78 |
| Vehicle assembly | 21.04 | 21.04 |
| Total | 100.00 | 72.28 |

With the assumption that the common body and chassis components will be mass produced and assembled the same way for both CV and HEV, the shares also provide an estimate of the retail price of these components in a midsize HEV. The analysis adds the cost of powertrain components to this common component price to yield an estimate of the potential HEV retail price.

### 3.2.2 Allocation of Indirect Costs

A vehicle's retail price includes costs that are not associated directly with its manufacturing, but were incurred in other areas of vehicle manufacturing and retailing. These costs include research and development, engineering, depreciation and amortization, corporate overhead, retirement and health benefits, vehicle distribution, advertising, dealer support, and profit. A vehicle's retail price structure can be broken down as shown in Table 3-3.

The cost of manufacturing, including assembly, typically accounts for about 50% of the retail price. This relationship can be extended to individual components. The analysis doubles the "factory gate" cost of a component manufactured by an OEM to arrive at its contribution to the vehicle retail price. Several components of the HEV, such as motor, motor controller and power electronics, and generator, are not likely to be produced by an OEM, however. These components would likely be procured from independent suppliers who would include warranty, R&D and engineering, and depreciation and amortizing costs in their component prices. These non-OEM HEV powertrain component prices are multiplied by a factor of 1.5 to arrive at their contributions to the vehicle retail price. The two multiplication factors are similar to those resulting from two other methodologies (Borroni-Bird 1996; OTA 1995).

The battery pack is a unique component. Though most likely to be procured from an independent supplier, it will require only assembly and testing. We assume that a multiplication factor of 1.15 applied to the battery pack cost is the minimum feasible cost multiplier for this expensive HEV component. It is lower than the 1.50 factor applied to the other outsourced components, and this admittedly low factor is used in the analysis.

**Table 3-3 Vehicle Manufacturing and Retail Price Structure**

| Major Cost Category | Cost Subcategory | Retail Price Share (%) By Major Category | Retail Price Share (%) By Sub-category |
|---|---|---|---|
| Production | | 67.0 | |
| | Manufacturing | | 50.0 |
| | Warranty | | 5.0 |
| | R&D and Engineering | | 6.5 |
| | Depreciation and Amortization | | 5.5 |
| Selling | | 23.5 | |
| | Distribution | | 20.0 |
| | Advertising and Dealer Support | | 3.5 |
| Administration and Profit | | 9.5 | |
| | Corporate Overhead | | 5.0 |
| | Retirement and Health Benefits | | 2.0 |
| | Gross Profit | | 2.5 |
| Total | | 100.0 | 100.0 |

Bear in mind that there are substantial differences among vehicle manufacturers in allocating indirect costs and determining retail prices. The prices derived by this analysis should be viewed as representative of average prices in a market operating in a manner similar to today's retail market, with the implicit assumption that manufacturers do not need to artificially subsidize HEVs in order to make them more acceptable to a risk-averse buying population.

### 3.2.3 Component Cost Information

The model uses a default midsize car cost of $22,500 for a vehicle capable of accelerating from 0-60 mph in 10 seconds. The resulting retail price equivalent share of the common components (between the conventional car and the HEV) is $16,270. The cost model then adds to this the estimated retail price contribution of the power unit and associated system, motor, inverter and power electronics, optional generator, transmission and/or gear drive, battery pack, system control, and other components for HVAC and electric auxiliaries.

The database containing the required component cost and performance information was developed using data from published sources coupled with technical judgment on learning and production volume-related improvements. The mass and power computation procedure uses the performance information and determines the ratings of each powertrain component. The cost modeling procedure uses the resulting power ratings and a set of equations to compute cost of the powertrain components. The information presented here is from the default database. The cost model uses four points in time. The first year assumes an annual production of 25,000 vehicles. The next three points in time represent rising annual production levels of 50,000-100,000, 100,000-200,000, and 250,000 or more. Thus, the cost estimation procedure does not estimate a potential HEV price for an initial production phase when several components would be manufactured in small quantities using less-than-optimal methods. In the description below, we use cost information for the 50,000-100,000 production level.

The component cost data reported below are "manufacturing" costs at the OEM factory gate. The final price to the consumer is computed through application of the above-mentioned multiplication factors.

#### 3.2.3.1 OEM Manufactured Components

The vehicle body, power unit and associated system, transmission and/or gear drive, system control, and HVAC and other components are assumed to be manufactured by the OEM. Table 3-4 shows fixed and variable terms used by the cost model.

**Table 3-4 Methodologies Used for Estimating OEM-Manufactured Component Costs**

| OEM Manufactured Component | Cost Function Type | Minimum Power (kW) | Fixed Cost ($) | Variable Cost ($/kW) |
|---|---|---|---|---|
| Power unit and system | Linear | [a] | 394 | 24.9 |
| Transmission: parallel | Step | 50[b] | 270 | 5.0 |
| Motor gear drive | Step | 50[b] | 85 | 1.7 |
| System control | Fixed | | 202 | |
| HVAC and other | Fixed | | 250 | |

[a] A minimum 20 kW power unit size assumed.
[b] The variable cost is zero up to this rating.

The second column in the table, "cost function type," indicates the method of cost computation. The methods are: (1) linear, in which fixed plus variable cost per kW values are used; (2) step, in which the cost remains unchanged until a minimum power rating listed in the third column is reached and, thereafter a variable cost per each additional kW is added; and (3) fixed, in which the cost does not change.

#### 3.2.3.2 Outsourced Electric Powertrain Components

The cost model assumes that all electric powertrain components, motor/generator and inverter/controller with power electronics, are procured from outside suppliers. We used data supplied by a DOE contractor to develop a set of linear functions (Duleep 1998). Table 3-5 shows fixed and variable terms used by the cost model.

**Table 3-5 Fixed and Variable Terms Used for Estimating Electric Drive Component Costs**

| Outsourced Component | Fixed Cost ($) | Variable Cost ($/kW) |
|---|---|---|
| Motor/generator | 200 | 13.7 |
| Inverter & power electronics | 425 | 19.0 |

#### 3.2.3.3 Outsourced Battery Pack

The battery cost numbers presented in this report are for the nickel metal hydride (NiMH) battery only. At the time of developing the HEV cost methodology, NiMH batteries had just been introduced in both Toyota's RAV-4 electric vehicle and its Prius HEV. The characteristics of these EV and HEV battery packs are very different. The EV battery pack has high specific energy while the HEV battery pack has high specific power. Since the motor in a power-assist (grid-independent) HEV is used intermittently and must be capable of producing high power for short periods of time (e.g., during maximum acceleration), its battery pack should be optimized for high power. Consequently, we assumed that the battery packs for grid-independent hybrids would be similar to the Prius's battery back. We also analyzed dual-mode (grid-connected) HEVs, which required battery packs with high energy storage as well as power output. For this vehicle type, we assumed an intermediate level of the nickel metal hydride battery with energy and power density characteristics in between the RAV-4 type and Prius type batteries. For estimating cost per kilowatt-hour, we used a report by the California Air Resources Board (CARB) Battery Advisory Panel (Kalhammer et al. 1995) and an ANL Delphi study (Vyas et al. 1997) for guidance. The characteristics and costs for the three batteries are shown in Table 3-6.

**Table 3-6 Nickel Metal Hydride Battery Characteristics and Costs**

| Battery Type | Specific Power (W/kg) | Specific Energy (W·h/kg) | Cost ($/kWh) |
|---|---|---|---|
| High power | 520 | 46 | 639 |
| Intermediate | 350 | 52 | 567 |
| High energy | 184 | 73 | 426 |

We note that the newly introduced U.S. version of the Prius has a significantly improved battery pack with specific power of 880 W/kg (Toyota 2000), 75% higher than the previous version. The cost of the new pack is reported as half of the previous version.[44]

### 3.2.4 Modeling Concerns

Projecting the costs and retail prices of future vehicles and vehicle components has tended to be problematic even for conventional vehicles, and there is substantial controversy about how much hybrid vehicles will cost. Obvious problem areas for this analysis include:

1. Direct information on component prices to original equipment manufacturers is rarely available; the OEMs generally hold this information as confidential. In addition, the manufacturers treat the prices they pay to component manufacturers as confidential information. Another potential source of information, retail prices for particular components, may be available only in limited situations, because many components of interest are integral to the vehicle and are not separately priced. Even when prices are

[44] Nakamura, N., Toyota Motor North America, Inc., personal communication.

available, they often do not reflect actual cost plus profit, but instead reflect the manufacturer's estimate of how the market values the components. Thus, the existing price data are of limited help in supporting cost projections.

2. Hybrid engine costs are problematic for two reasons: first, they are extrapolations from larger, more powerful engines designed for CVs; and second, hybrid duty cycles are different from CV cycles, so the design of a purpose-built hybrid engine will be different from that of an engine built for a CV. In the Prius, for example, Toyota has restricted the rpm level of the engine and has been able to cut costs by using some lighter, less expensive components as a result.[45]

3. The electric drive components presently are built in small quantities at high prices that do not reflect savings associated with mass production. Further, there is a vigorous R&D program aiming at improving (altering) the designs for key components, further complicating the task of projecting costs and retail prices. The HEVCOST methodology ignores current costs and estimates high volume costs by starting from the materials in the components, building in normal markups. However, uncertainties associated with changes in materials, production methods, and power densities (yielding reductions in materials) remain.[46]

4. Estimating fuel and electricity costs for both grid-independent and grid-dependent hybrids run into a number of problems. We have modeled HEV onroad fuel economy by multiplying the ADVISOR-estimated corporate average fuel economy (CAFE) values by the current EPA onroad degradation factor of 0.85 (we used a lower value, 0.80, as the degradation factor for conventional vehicles; this reflects the shift in driving to more congested conditions, a shift that will have less impact on HEVs). However, the 0.85 degradation factor was developed for vehicles with conventional drivetrains and is unlikely to be accurate for HEVs. We have adopted the 0.85 degradation factor as a default value for HEVs until better data are available. Another concern for grid-dependent HEVs is uncertainty about the percentage of energy use supplied by the grid.

## 3.3 References

Borroni-Bird, C., 1996, *Automotive Fuel Cell Requirements*, Proceedings of the 1996 Automotive Technology Development Customers' Coordination Meeting, U.S. Department of Energy, Office of Transportation Technologies, Washington, D.C.

Cuenca, R.M., L.L. Gaines, and A.D. Vyas, 2000, *Evaluation of Electric Vehicle Production and Operating Costs,* Argonne National Laboratory Report ANL/ESD-41, Argonne, Ill.

---

[45] Duleep, K.G., unpublished report to U.S. Department of Energy on Prius costs, 1998.

[46] As noted above, the new Prius battery back is much smaller and lighter than the previous version, implying that cost estimates based on the previous pack's power density and weight would be much too high.

Duleep, K.G., 1998, *Briefing on Technology and Cost of Toyota Prius*, Energy and Environmental Analysis, Inc., Arlington, Va.

FHWA, 1997, *1995 Nationwide Personal Transportation Survey (NPTS): Compact Disk and Code Book,* U.S. Department of Transportation, Federal Highway Administration, Washington, D.C.

Hellman, K.H., M.R. Peralta, and G.K. Piotrowski, 1998, *Evaluation of a Toyota Prius Hybrid System (THS)*, U.S. Environmental Protection Agency Technical Report EPA 420-R-98-006, Ann Arbor, Mich., Aug.

Kalhammer, F.R., A. Kozawa, C.B. Moyer, and B.B. Owens, 1995, *Performance and Availability of Batteries for Electric Vehicles: Report of the Battery Technology Advisory Panel,* California Air Resources Board, El Monte, Calif.

Nakamura, N., Toyota Motor North America, Inc., personal communication.

OTA, 1995, *Advanced Automotive Technology: Visions of a Super-Efficient Family Car,* United States Congress, Office of Technology Assessment Report OTA-ETT-638, Washington, D.C.

Reuyl, J.S., and P.J. Schuurmans, 1996, NEVCOR, Inc., *Policy Implications of Hybrid-Electric Vehicles,* Final Report to NREL, Figure 11, April 22.

Santini, D., and J. Anderson, 1993, *Determinants of Multiple Measures of Acceleration*, SAE 931805, SAE Transactions.

Santini, D., J. Anderson, J. He, S. Plotkin, A. Vyas, and D. Bharathan, 1999, *Gasoline-Fueled Hybrid vs. Conventional Vehicle Emissions and Fuel Economy*, Annual Meeting of the Air and Waste Management Association, St. Louis, Mo., June 20.

Vyas, A.D., H.K. Ng, D.J. Santini, and J.L. Anderson, 1997, *Electric and Hybrid Electric Vehicles: A Technology Assessment Based on a Two-Stage Delphi Study*, Argonne National Laboratory Report ANL/ESD-36, Argonne, Ill.

Vyas, A., R. Cuenca, and L. Gaines, 1998, *An Assessment of Electric Vehicle Life Cycle Costs to Consumers,* Proceedings of the 1998 Total Life Cycle Conference, pp. 161-172, SAE International Report P-339, Warrendale, Pa.

Wang, M.Q., S. Plotkin, D.J. Santini, J. He, L. Gaines, and P. Patterson, 1997, *Total Energy-Cycle Energy and Emissions Impact of Hybrid Electric Vehicles*, Presented at the 14th International Electric Vehicle Symposium, Orlando, Fla., Dec. 15-17.

Wipke, K.B., M.R. Cuddy, and S.D. Burch, 1999, *ADVISOR 2.1: A User-Friendly Advanced Powertrain Simulation Using a Combined Backward/Forward Approach*, National Renewable Energy Laboratory Technical Report NREL/JA-540-26839, Sept.

# Section 4
# Results of Vehicle Modeling

This section describes the results of the Advanced Vehicle Simulator (ADVISOR) and Hybrid Electric Vehicle Component Sizing Cost and Vehicle model (HEVCOST) modeling of vehicle energy use and cost (see discussion in Section 3 for a discussion of why we have chosen not to present criteria emissions results).

## 4.1 Description of the Vehicles Evaluated

The HEVTA has focused on a midsized passenger car, primarily because this is the focus of the current Partnership for a New Generation of Vehicles (PNGV) research and because the results can be applied, with some caution and modification, to most of the light-duty vehicles in the U.S. fleet. The current vehicles on which the HEVTA vehicles are based – the Chrysler Intrepid, Chevrolet Lumina, and Ford Taurus – are assumed to be slightly downsized (in external dimensions) for the timeframe of the analysis, 2005-2020. They are also assumed to have advanced low rolling resistance tires and greatly improved aerodynamics.

For sizing, we have chosen the current Chrysler Cirrus and Chevrolet Malibu as having the approximate external dimensions of a future midsize car that has undergone a process of interior space and structural redesign accompanied by substantial weight reduction. The current cars weigh about 1,418 kg (3,125 lb). By 2010, with an ultralight steel (ULS) body, these cars would be expected to weigh about 1,255 kg (2,767 lb), with the body and chassis (basically, the car without its drivetrain) assumed to contribute 73.5% of the vehicle mass, or 922 kg (2,029 lb). When these vehicles are converted to hybrid electric vehicles (HEVs), their body and chassis weight is assumed to increase by 5% to account for any additional structural strength needed to support the battery pack and power-electronic components.[47]

As discussed previously, to obtain a fair comparison between hybrid and conventional vehicles, we have assumed that all the vehicles share the same body characteristics and similar performance, measured as zero to 60 mph acceleration (Z60) time. All of the vehicles are essentially identical except for differences in their drivetrains and the 5% structural weight difference. The hybrids also must satisfy a gradeability requirement, although the conventional vehicles have better gradeability due to their larger, more powerful engines. Table 4-1 shows the basic body characteristics assumed for the 2010 and 2020 vehicle.

[47] Note that this 5% factor is somewhat arbitrary, for two reasons: first, it is possible to design the battery pack in such a way that it becomes an integral and supporting part of the body structure, thus reducing or eliminating the need for added structural weight; and second, the size and weight of the battery pack and electronic components, thus the added structural weight required, will vary significantly depending on the vehicle's performance requirements and on whether it is expected to be capable of operating all-electrically, with some recharging from the grid.

**Table 4-1 Midsize HEV Characteristics**

| Vehicle Characteristics | 2010 | 2020 |
|---|---|---|
| **Body and chassis mass in kg (lb in parenthesis)** | | |
| Ultralight steel body | 969 (2,136) | 959 (2,114) |
| **Aerodynamic and rolling** | | |
| Frontal area (square meters) | 2.06 | 2.01 |
| Coefficient of drag (Cd) | 0.26 | 0.24 |
| Coefficient of rolling resistance (Cr) | 0.0075 | 0.0065 |

We examine a number of different types of hybrid design, including:

***Parallel grid-independent full hybrid,*** with engine sized to provide the power to maintain gradeability requirements, and battery/motor sized to provide adequate boost to the engine to allow attainment of the Z60 requirement.

***Parallel grid-independent mild hybrid,*** with less battery and motor power and more engine power than the parallel grid-independent hybrid. Engine power is precisely midway between the conventional vehicles (CVs) and full hybrid's engine power, with battery and motor power consequently sized to provide enough boost to satisfy the Z60 requirement.

***Series grid-independent full hybrid,*** with engine and electric motor (continuous rating) sized for gradeability, battery sized to provide boost for acceleration requirements, and electric motor (maximum power) sized for full acceleration power requirements.[48]

***Parallel and series grid-dependent hybrids,*** designed to operate part of the time as full electric vehicles, so battery and electric motor are sized to satisfy a separate electric vehicle (EV) acceleration requirement, and the engine is sized to provide full HEV gradeability. For the parallel hybrids we examined, this combination tends to allow especially rapid acceleration when both engine and battery/motor are engaged simultaneously, because the battery and motor are considerably larger than those found in a parallel grid-*independent* hybrid.

For the grid-independent vehicles, we examine power levels that will allow Z60 times of 8, 10, and 12 seconds. The original PNGV guidelines call for Z60 times of 12 seconds, but this value has been outrun by changes in the fleet. The current average Z60 time for midsize cars is 10.5 seconds, vs. 11.4 seconds in 1994 when the guidelines were established (Heavenrich and Hellman 1999). Trends of increasing power and decreasing Z60 times appear to be robust. For grid-connected vehicles, we examine power levels that will allow *all-electric* Z60 times of 12, 14, and 16 seconds. Keeping all-electric Z60 times for these vehicles more modest makes sense because the powerful and very expensive electric motors needed to allow faster acceleration

[48] In other words, there are two separate sizing criteria for the electric motor. Although the gradeability criterion requires less power than the acceleration criterion, the motor's continuous power rating will be lower than its peak rating. Therefore, actual motor size may be determined by either the acceleration or the gradeability criterion, depending on motor design and the gradeability and acceleration criteria used.

would make these vehicles extremely expensive (they are already considerably more expensive than the grid-independent hybrids).

The drivetrain components of both conventional and hybrid vehicles will likely be substantial improvements over those available today. For example, it seems quite possible that, by 2010, the engines driving both conventional and hybrid vehicles will be mature versions of recently-introduced direct injection stratified charge (DISC) gasoline engines, direct injection (DI) diesels (if emissions problems are solved), or other advanced technologies. Recent progress in electrical drive technology implies that batteries, motors, and power electronics will have both higher efficiency and higher specific power than those available today. All such developments will increase the efficiency of hybrid vehicles, although use of advanced engines and transmissions in conventional vehicles may shrink the relative efficiency advantage of the hybrids (see Section 2.5.5).

Tables 4-2 and 4-3 show the assumed characteristics of the batteries and other hybrid drivetrain components for 2010 and 2020. The study team decided not to try to simulate an advanced engine, in part because appropriate engine maps were not available. The base engine, from which the HEV and CV engines were scaled, is a 1994 version of a 63 kW (85 horsepower) single overhead cam (SOHC) 1.9-L Saturn engine. The battery characteristics are based on the results of a Delphi study conducted by ANL as well as published characteristics of the batteries used in Toyota’s Prius hybrid (Japanese market version[49]) and RAV-4 electric vehicles. The motor, generator, and inverter characteristics are based on the performance of a Unique Mobility SR218H permanent magnet motor and CA40-300L inverter, with assumed improvements over time. The efficiencies shown in Table 4-3 are those attained during high-power acceleration (that is, during peak loading of the components) and are used to determine the battery power capacity needed to allow the vehicle to achieve acceleration goals. Future analysis will explore the effects of changing the various component assumptions.

**Table 4-2 Nickel Metal Hydride Battery Characteristics**

| Battery Characteristic | High-Energy/ Low-Power | | Intermediate | | Low-Energy/ High-Power | |
|---|---|---|---|---|---|---|
| | 2010 | 2020 | 2010 | 2020 | 2010 | 2020 |
| Specific power (W/kg) | 184 | 203 | 350 | 386 | 520 | 573 |
| Specific energy (Wh/kg) | 73 | 79 | 54 | 58 | 46 | 50 |
| Cost ($/kWh) | 426 | 382 | 533 | 478 | 567 | 508 |
| Cost ($/kW) | 169 | 149 | 82 | 72 | 50 | 44 |

[49] The version of the Prius introduced into the U.S. market has an upgraded battery pack attaining a specific power of 880 W/kg, versus the earlier Japanese version’s 500 W/kg. We based our battery on the earlier Japanese version.

**Table 4-3 Specific Power and Efficiency Values for HEV Drivetrain Components**

| Component | Type | 2010 | 2020 |
|---|---|---|---|
| **Specific Power (W/kg)** | | | |
| Motor and generator | Permanent magnet | 1,300 | 1,400 |
| Auxiliary power unit | Gasoline | 330 | 340 |
| Motor with inverter | | 1,025 | 1,110 |
| Transmission (parallel HEV) | | 1,320 | 1,360 |
| Transmission (series HEV) | | 1,650 | 1,700 |
| **Efficiency (%)** | | | |
| Motor and inverter | Permanent magnet | 90 | 93 |
| Battery (one-way) | Nickel metal hydride | 93 | 95 |
| Transmission | | 93 | 95 |

## 4.2 Vehicle Control Strategy

Ideally, the computer onboard a hybrid vehicle will respond to the driver's power demands by combining engine and battery power capabilities in an optimum manner, with "optimum" defined as a predetermined function of energy use and emissions. For example, optimum might be defined as minimizing fuel consumption with emissions held below Tier 2 limits. To accomplish this, the computer would have to continuously examine the energy losses associated with each path for tractive power (e.g., engine to transmission to differential to wheels, battery to motor to reduction gear to differential to wheels) and select the most efficient combination that delivered the required power while checking to ensure that emissions constraints were not exceeded. The National Renewable Energy Laboratory (NREL), the developer of ADVISOR, has examined such control strategies (Johnson 2000).

Up to this point, the Hybrid Electric Vehicle Technology Assessment (HEVTA) analyses have used a simpler control strategy. For parallel vehicles, the motor is used to launch the vehicle and provides all torque below a specified launch speed, with the engine turned off. Above that speed, the engine is turned on and used as a load follower, generally satisfying all torque requirements up to the engine's maximum capability. The exception occurs if torque demanded falls below a set limit, for example during a downhill coast or during braking, and the engine shuts off. When the engine is turned on, the motor assists the engine only if the desired torque is higher than the engine's maximum capability, e.g., during high acceleration. During braking, the motor provides all braking force up to its maximum capacity, feeding the electricity generated to the batteries; the mechanical brakes provide any additional braking force needed. Finally, if the battery state of charge (SOC) goes below a specified lower bound, the engine deliberately increases its torque output above the level demanded by the tractional load and accessory power load, with the excess torque passing through the motor (acting as a generator) to charge the battery.

## 4.3 Driving Cycles

All of the vehicles are tested under a variety of driving conditions to evaluate HEV costs and benefits under a range of conditions, identify potential market niches for HEVs, and evaluate

HEV and CV performance on the standardized government tests used to measure "official" vehicle fuel economy. These driving conditions are represented quantitatively by "driving cycles."

Driving cycles are defined by second-by-second profiles of vehicle speed; Figures 4-1a-e show five of the seven cycles examined in our analysis. Each profile determines the second-by-second power requirements of the vehicle being tested, which in turn (in conjunction with vehicle efficiency attributes) determine the vehicle operation regimes (rpm, torque, etc.) and vehicle fuel economy and emissions performance.

Standard driving cycles are used for certifying motor vehicles for compliance with fuel economy and emissions regulations. In the United States, emissions compliance for a light-duty vehicle is measured by driving the vehicle (on a dynamometer) over a driving cycle called the federal testing procedure (FTP, see Table 4-4). Under this procedure, the vehicle is first driven through the FUDS (federal urban driving schedule) cycle, hot-soaked for about 10 minutes, and then driven through the first 505 seconds of the FUDS. Emissions are collected in three separate bags. The first bag covers the first 505 seconds of the FUDS, which represents cold-started operations; the second bag covers the rest of the FUDS, which represents hot-stabilized operations (the bag is switched with the engine running); and the third bag covers the repeated (after the 10-minute hot soak) first 505 seconds of the FUDS, which represents hot-started operations. Emissions of the three bags are weighted together and combined with the results of a supplementary driving schedule recently added to the testing (see discussion below) to determine if a given vehicle meets applicable emission standards.

For compliance with corporate average fuel economy (CAFE) standards, the fuel economy of motor vehicles is measured under both the FTP and the Highway cycle. A composite city/highway fuel economy is calculated by applying the formula

$$1/\text{fuel economy} = (0.55/\text{FTP fuel economy}) + (0.45/\text{Highway fuel economy})$$

The FUDS and Highway cycles were developed in the early 1970s to represent urban and highway driving, respectively. However, the Highway cycle was developed with a focus on accommodating the capability of vehicle dynamometer testing facilities available at the time, with less focus on representing actual freeway driving patterns. Also, since the late 1980s, studies have found that both the FUDS and the Highway cycle under-represent the aggressiveness of actual on-road driving patterns (Austin et al. 1992; U.S. EPA 1993). Consequently, the U.S. EPA and California Air Resources Board (CARB) have made efforts to identify on-road driving behaviors and develop driving cycles that are more representative of real-world driving (Effa and Larsen 1993; Enns et al. 1995). The Representative No. 5 cycle (REP05), developed by the U.S. EPA using data from Atlanta, Baltimore, and Spokane, is intended to represent aggressive urban freeway driving patterns. The U.S. No. 6 cycle (US06) is a short version of the REP05 which EPA has included as an additional bag (Bag 4) in a revised FTP to address emission impacts of aggressive driving (U.S. EPA 1995). Compared with the FUDS and the Highway cycle, these two newly developed cycles have higher average speeds, maximum speeds, maximum acceleration rates, and maximum deceleration rates.

**Table 4-4  Characteristics of Seven Driving Cycles**

| | NYCC | JAPAN10/15 | FUDS | FTP | US06 | HWY | REP05 |
|---|---|---|---|---|---|---|---|
| Time duration, sec | 600 | 660 | 1372 | 1877 | 600 | 765 | 1400 |
| Distance, miles | 1.2 | 2.59 | 7.5 | 11 | 8 | 10.2 | 20 |
| Avg. Speed, mph | 7.1 | 14.1 | 19.5 | 21.2 | 48 | 48.2 | 51.5 |
| Max. Speed, mph | 27.7 | 43.5 | 56.7 | 56.7 | 80.3 | 59.9 | 80.3 |
| Max. decel, mph/sec | -5.9 | | -3.3 | -3.3 | -6.9 | -3.3 | -7.1 |
| Max. accel, mph/sec | 6 | 1.6 | 3.3 | 3.3 | 8.5 | 3.2 | 8.5 |

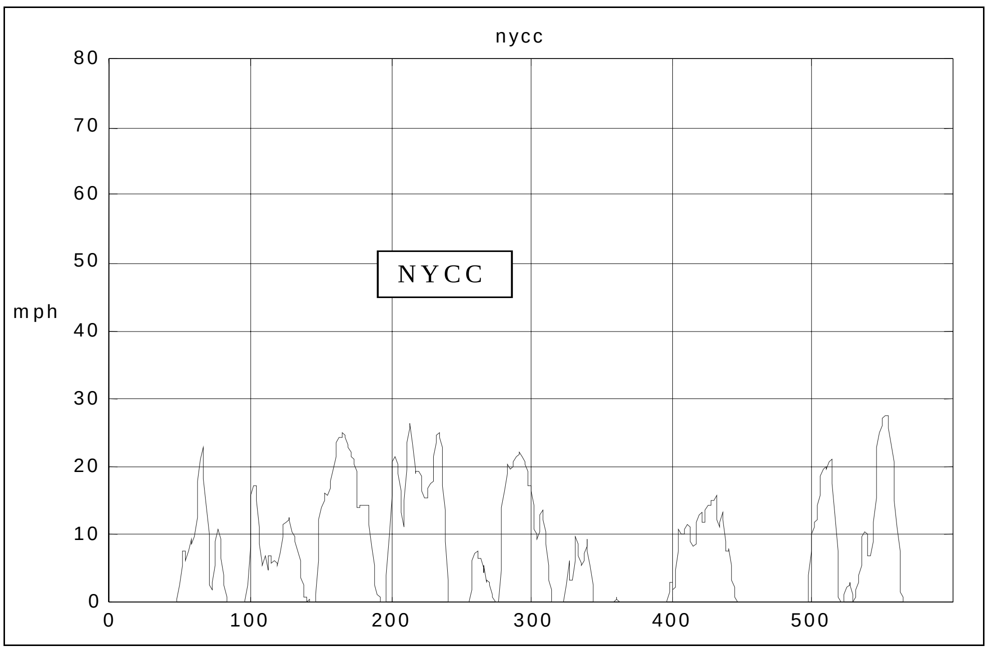



**Figure 4-1a  Speed Profile of the New York City Cycle**

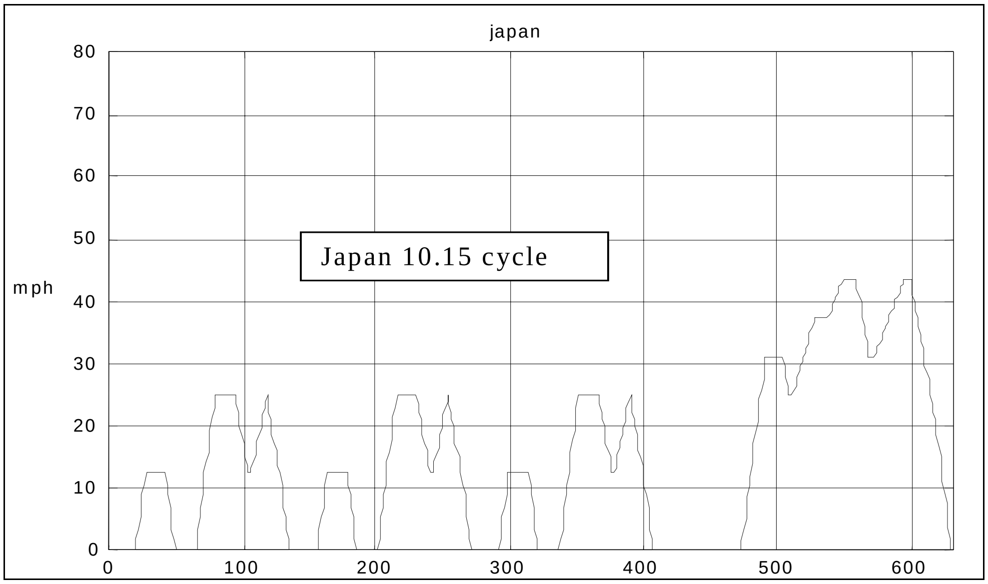



**Figure 4-1b Speed Profile of the Japan 10/15 Cycle**

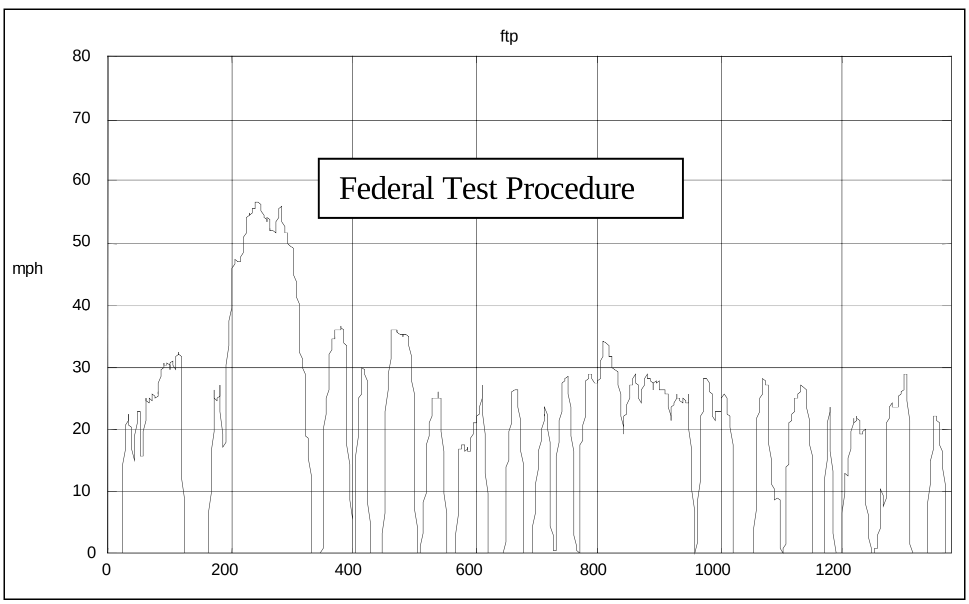



**Figure 4-1c Speed Profile of the Federal Test Procedure (FTP)**

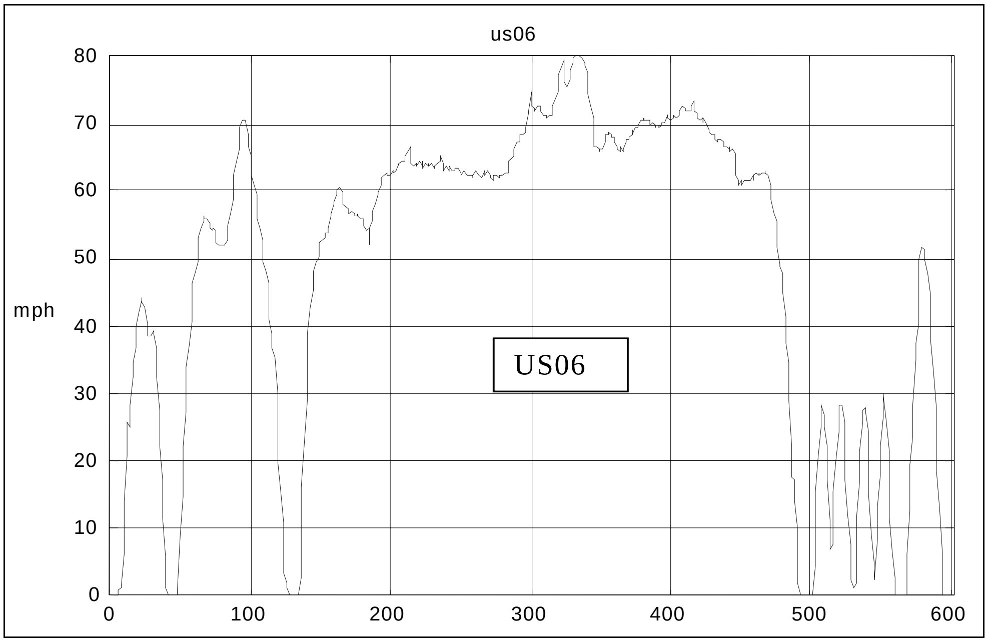



**Figure 4-1d Speed Profile of the U.S. No. 6 Cycle**

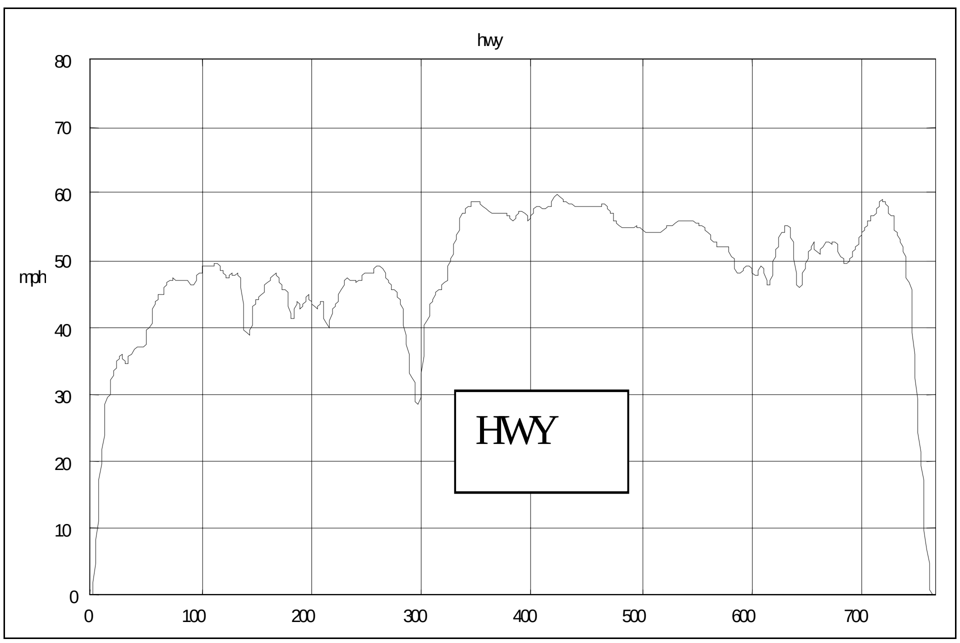



**Figure 4-1e Speed Profile of the Highway Cycle**

Table 4-4 presents key characteristics of the above-described seven cycles, which are used in the HEVTA to evaluate each CV and HEV.

Other cycles have been developed to represent driving patterns in downtown areas of large cities. The New York City cycle (NYCC), developed in the 1970s, was intended to represent particularly congested inner cities. A sixth cycle, the Japan 10/15 cycle, also represents congested driving. It is particularly relevant for an evaluation of hybrid vehicles because the two hybrids that have been commercially introduced thus far – Prius and Insight – are both Japanese and had, until 1999, been tested only on this cycle.

## 4.4 Other Critical Assumptions

Most of the ADVISOR modeling examined 2010 vehicle configurations. Because of the (assumed) sharp changes in HEV purchase costs from 2005-2020, we wished to examine how life cycle costs changed over this same time period. To roughly approximate the changes in fuel costs over time, we ran ADVISOR for parallel grid-independent hybrids and their competing CVs using projected 2020 vehicle parameters (which included lighter weight and more efficient electrical components than were presumed to be available in 2010). The ratio of ADVISOR-derived 2020 mpg and fuel costs to 2010 mpg and fuel costs for the parallel grid-independent hybrids and CVs was presumed to apply to all other models (series grid-independent, parallel mild hybrids, and both parallel and series grid-connected HEVs). Further, 2005 and 2015 values for *all* vehicles were estimated by interpolating from the 2010 and 2020 values.

## 4.5 Estimating Energy Use From Grid-Connected HEVs

As discussed in Section 3.1.2.7, uncertainties in the trip characteristics and battery management strategies of grid-connected HEVs complicate the accurate estimation of their energy use, particularly the split between grid-powered and fuel-powered operations. At this point, we have modeled grid-connected HEVs in hybrid operation (that is, after the period of EV operation and engine recharge) for the six driving cycles discussed above, and in EV operation over the FUDS cycle. Aside from reporting on these results, we will estimate average energy use results based on the assumption that the grid supplies energy for an average daily distance equal to 60% of the vehicle's EV range, with the remainder of daily travel supplied by on-board fuel. In measuring life cycle energy costs, we assume that both CVs and HEVs in hybrid operation travel the CAFE cycle, and grid-connected hybrids in EV mode travel the FUDS cycle.[50]

The 60-percent recharge value was obtained by examining the three possible options for a grid-connected HEV's daily travel, assuming that the battery SOC range for hybrid operation is either 0.4-0.5 or 0.5-0.6[51]:

---

[50] This is primarily because our initial modeling runs modeled the EV-mode energy use only for the FUDS cycle. In the future, we will model the EV-mode energy use over the range of driving cycles, and make our vehicle-to-vehicle comparisons using multiple cycles.

[51] This is a conservative value for the state-of-charge range, selected out of concern for battery longevity. See discussion in Section 3.1.2.7.

1. *Days when the vehicle travels less than its EV range R:* All miles are recharged by the grid; the vehicle is awarded something less than R grid-miles on those days (zero if the vehicle does not travel at all).

2. *Days when the vehicle travels more than its EV range but less than the distance to full hybrid operation:* For 0.4-0.5 SOC operation, the vehicle is recharged by the grid from 0.325 SOC[52] to 0.95 SOC, or 0.625 SOC, or 0.625/.75 = *0.83R*; for 0.5-0.6 SOC operation, the vehicle is recharged from 0.375 SOC to 0.95 SOC, or 0.575 SOC, or *0.77R.*

3. *Days when the vehicle travels farther than the distance to full hybrid operation:* The vehicle is recharged from the grid, for 0.4-.5 SOC operation, from 0.45 SOC to 0.95 SOC, or 0.5 SOC, or 0.5/0.75 = *0.67R;* for 0.5-0.6 SOC operation, the vehicle is recharged from 0.55 SOC to 0.95 SOC, or *0.53R.*

Given these three options, daily grid-energized operations for 0.6R miles seems a reasonable value, although definitive assumptions about the type of driving patterns most likely for such vehicles would, of course, push this estimate in one direction or the other. Also, if the battery SOC range for hybrid operation can be kept low (e.g., at 0.2-0.3 SOC) without unduly compromising battery longevity, the fraction of grid-recharged miles will be somewhat higher than 0.6R.

## 4.6 Model Results

The full results of the ADVISOR and HEVCOST modeling are presented in the tables in Appendix A. The following discussion presents some key conclusions drawn from these results.

1. **HEVs gain the largest fuel economy advantage over CVs on the slowest driving cycles.**

Figure 4-2a shows how hybrids' fuel economy advantage over conventional vehicles depends sharply on driving cycle. As the figure shows, HEVs appear to do best, in relative terms, on slow cycles with a great deal of stop-and-go traffic.

[52] Assuming that, on average, the vehicle is shut down when the battery SOC is midway between 0.2 SOC and the middle of hybrid operation, 0.45 SOC.

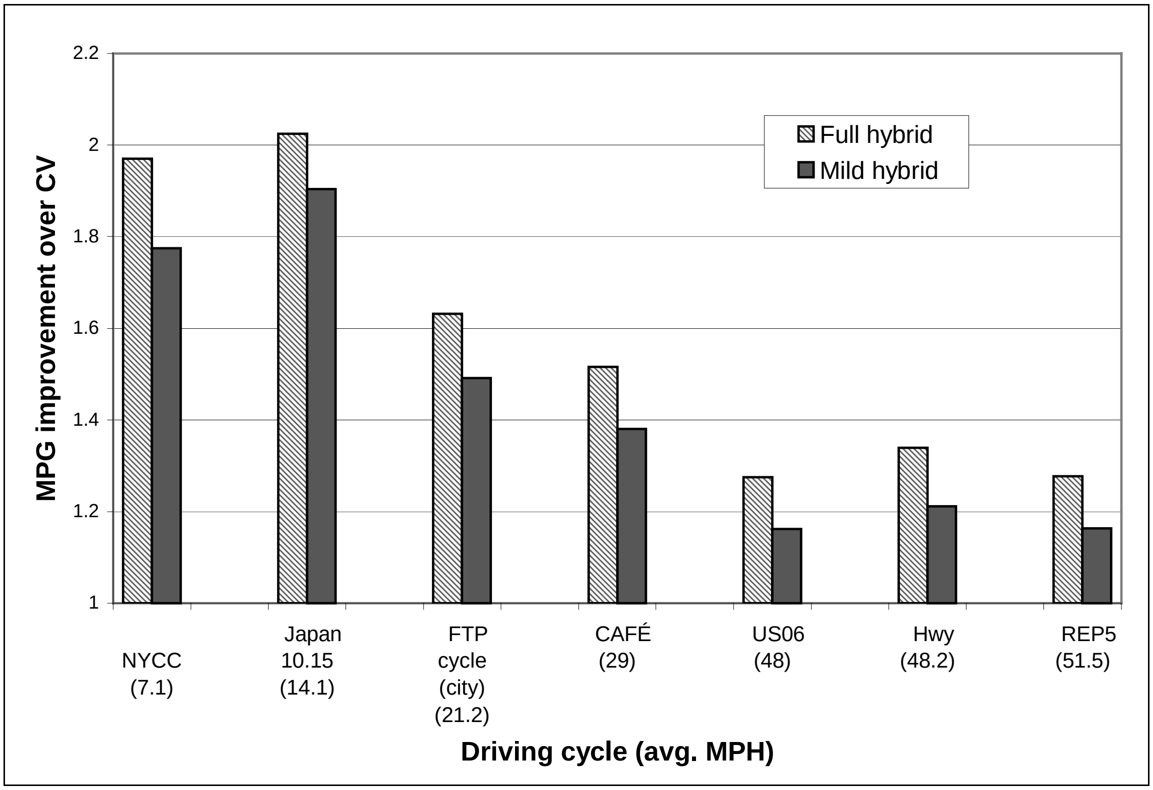



**Figure 4-2a HEV Fuel Economy Advantage over CVs, for Different Driving Cycles (2010 parallel grid-independent ultralightweight steel [ULS] HEV, 10-second Z60)**

These results are logical when one examines the sources of fuel savings by HEVs. We expect hybrid vehicles to excel relative to CVs under driving conditions where CVs lose substantial amounts of energy in ways that hybrids do not. In slow, congested traffic, CVs lose large amounts of energy to braking losses, idling, and engine operation at low efficiency points. Hybrids recapture part of braking losses, minimize idling by turning off the engine when the vehicle isn't moving, and, in most hybrid configurations, avoid using the engine at its lowest efficiency points either by using only the battery and motor to drive the vehicle at very low speeds, or always keeping engine power high enough to remain efficient, bleeding off excess power to recharge the battery.

The modeled parallel grid-independent ultralightweight steel (ULS) hybrid approximately doubles the efficiency of a comparable CV on the very slow NYCC and Japan 10/15 cycles. This result is compatible with the reported fuel economy gain of the Toyota Prius hybrid on the Japanese cycle. Although these cycles are far from typical for U.S. driving, the result implies that hybrids will be particularly effective in congested city driving, for example, for urban taxicabs, transit buses, and even garbage trucks,[53] all of which stop frequently and operate during much of the day in crowded, slow traffic.

In contrast, the hybrids' fuel economy gains on the Highway and other fast cycles are far more modest – about 30% for the full hybrid and 20% for the mild hybrid, for the 10-second Z60 case. If anything, these gains seem high, because there is little braking and idling on the cycle, and engines in conventional drivetrains tend to run fairly efficiently at highway speeds, yielding less opportunity for savings compared to city driving, especially when the hybrid's weight gain is factored in. In fact, we would expect that most of any (Highway cycle) savings to be had from hybridization would come from the effects of engine downsizing, that is, on the efficiency effects of running at a higher percentage of the engine's rated power. Because of our initial skepticism about the highway cycle fuel economy results, we examined the effects of engine downsizing on conventional drivetrains (see Section 4 Appendix B) to gain some perspective on the relative benefits of such downsizing. As shown in Appendix B, the ADVISOR Highway results seem reasonably consistent with the mpg benefits associated with engine downsizing in CVs.

At first glance, the implications of this conclusion are that maximum fuel savings from hybrids would be obtained from drivers in congested urban areas. This conclusion must be tempered by the possibility that vehicle miles traveled *per vehicle* may vary among different kinds of areas. Santini and Vyas (1999) point out that different data sources (e.g., the Nationwide Personal Transportation Survey, cross-national data on miles driven/vehicle and average driving speeds) imply that the number of hours/day most drivers are willing to spend in their cars falls within a fairly narrow range. On a fixed time budget, vehicle miles traveled per vehicle varies inversely with average driving speed. In other words, personal vehicles based in congested urban areas may accumulate fewer miles of driving per year than suburban-based vehicles. Newman and Kenworthy (1989) previously reached precisely this conclusion. Thus, drivers of hybrid vehicles living in congested areas may drive less than hybrid owners living in suburban areas, partially nullifying the large fuel economy advantage they hold over comparable CVs.

Figure 4-2b shows the implications in fuel savings of assuming that vehicles are driven the same number of hours per day, by showing the gallons of gasoline saved by full and mild hybrids (compared to a CV) in 10 hours of driving. With this assumption, full hybrids' superiority in slow, stop-and-go urban driving essentially disappears; driving in higher speed conditions saves more gasoline even though gallons saved per mile goes down. For mild hybrids, the relationship between type-of-driving and fuel savings is a bit different, with savings on the slowest cycles showing a small advantage.

[53] In a separate analysis for the DOE Office of Heavy Vehicle Technologies, ANL has evaluated the effect of hybridizing Class 3-7 heavy-duty vehicles. See An et al. (2000).

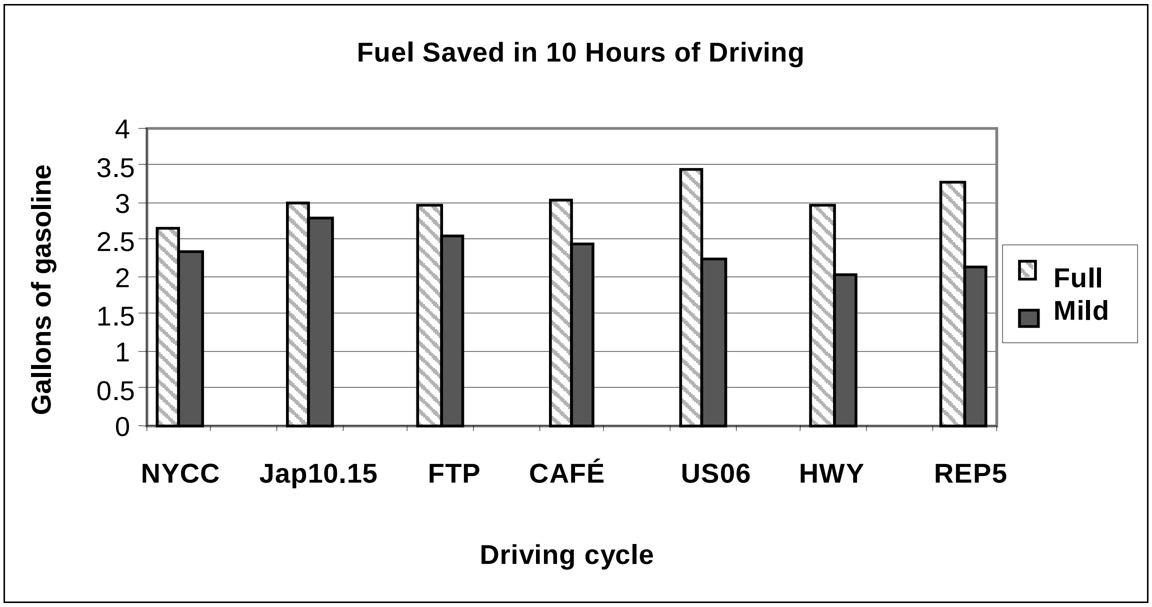



**Figure 4-2b HEV Fuel Economy Advantage over CVs, Measured in Gallons Saved in 10 Hours of Driving**

2. **Parallel HEVs are likely to be more efficient than series HEVs, with both having fuel economy that is less sensitive to performance than a CV.**

Figure 4-3 shows the fuel economy of comparably-performing CVs and grid-independent HEVs as a function of acceleration performance.

Our modeled results show a clear efficiency advantage for parallel HEVs over series HEVs. Examining the way the alternative configurations use energy, the clearest difference is that the parallel HEV's engine drives the wheels directly through the differential and transmission for much of its operation, whereas the series HEV's engine must first generate electricity through the generator and then drive the wheels through the motor. The parallel HEV's direct engine/ transmission/differential route is more efficient than the series HEV's engine/generator/motor route, accounting for much of the efficiency difference between the two vehicles. Further, the series vehicle will likely be heavier than the parallel vehicle because the series' motor is by far the more powerful of the two, having to provide all motive power to the vehicle, and the series' engine is also somewhat larger (compared to the full hybrid) to compensate for the less efficient driveline. The series hybrid may, however, be capable of capturing more braking energy, because the larger motor is capable of exerting far more braking force, leaving less work for the mechanical brakes; this capability gives the series hybrid a small offset to the efficiency advantages of parallel hybrids.

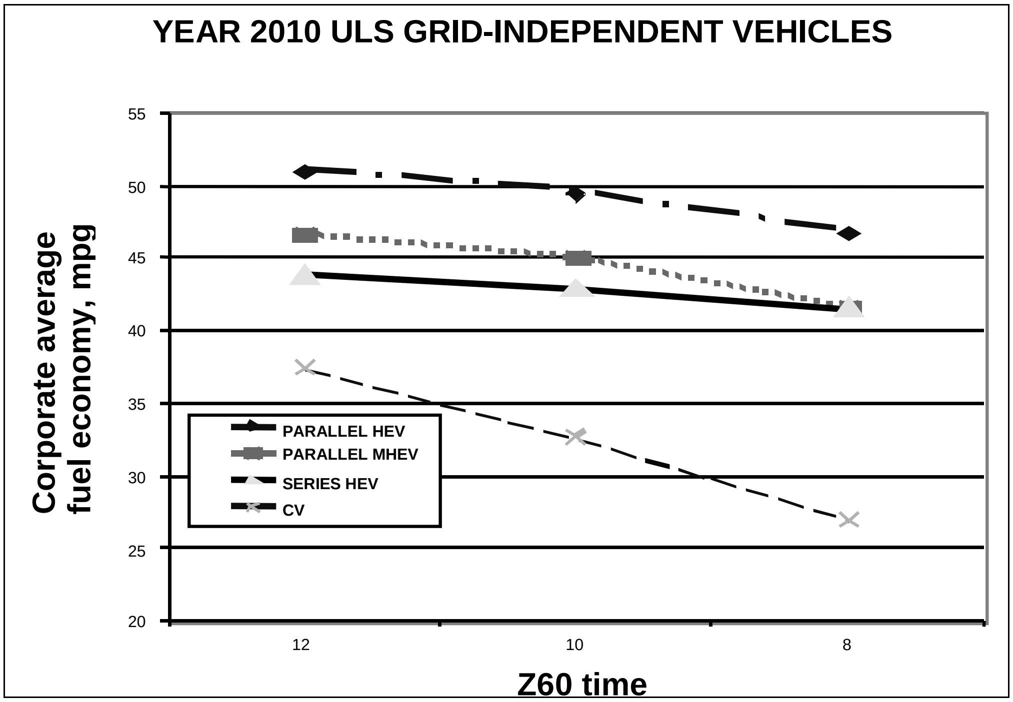



**Figure 4-3 Fuel Economy Variation of CV and HEVs with Z60 Requirements (year 2010 ultralight steel grid-independent vehicles)**

We emphasize that our results apply to passenger cars in normal driving. Urban buses may yield different results because their stop-and-go, low-speed duty cycles may make the series hybrid configuration more competitive.[54]

The results also show that hybrids' fuel economy levels will not vary with vehicle performance to the same extent as do CVs. In going from a 12-second Z60 time to an 8-second time, the CV's fuel economy loss is 28.3%, in contrast to the mild (parallel) hybrid's 10.7%, the full (parallel) hybrid's 8.4%, and the series hybrid's 5.5%. The results generally conform well with our understanding of how CVs and hybrids use energy. In a CV, a more powerful engine used to obtain better acceleration performance will, aside from adding weight, have increased idle losses and tend to operate further away from its maximum efficiency point during most driving (assuming identical engine design). This yields a significant penalty in fuel economy. Hybrids minimize idle losses, so the increased idle losses that occur when a CV engine gets larger should not occur with a hybrid. This, plus the fact that the mild hybrid's engine increases in power less than does the CV's engine (the mild hybrid gains performance by increasing *both* engine power and motor/battery power) may account for why the mild hybrid pays such a small penalty in fuel economy. Finally, both the full (parallel) hybrid and series hybrid designed according to our convention – engine sized for gradeability, motor/battery for acceleration – gain acceleration performance primarily by increasing motor and battery power, so their engines will

[54] We note that the two hybrid buses tested in Northeast Advanced Vehicle Consortium, 2000, were both series hybrids.

get only slightly bigger. Thus, there will be little in the way of added losses from a decline in engine efficiency over the driving cycle. The major fuel economy penalty will come from added weight, which is a small increment.

3. **Hybrids' mpg improvement over CVs increases as the acceleration times go down.**

Figure 4-4a shows the degree to which our simulated HEVs attain a fuel economy improvement over CVs, as a function of acceleration time.

An obvious result of the CV fuel economy sensitivity to acceleration requirements and the hybrids' *lack* of such sensitivity is that the hybrids' relative fuel economy advantage over CVs increases as acceleration times decrease. In other words, the more powerful the vehicle, the more fuel hybridization will save. This is important because PNGV's original 12-second 0-60 mph acceleration time target has become outmoded. The U.S. fleet has grown increasingly powerful and faster during the past decade, and 10 seconds now seems a more likely target for a midsized car *right now*, and 8 seconds might well be the target by the time PNGV cars are actually marketed. Thus, in terms of acceleration performance, the market is driving light-duty vehicles (LDVs) in a direction that is favorable for hybridization.

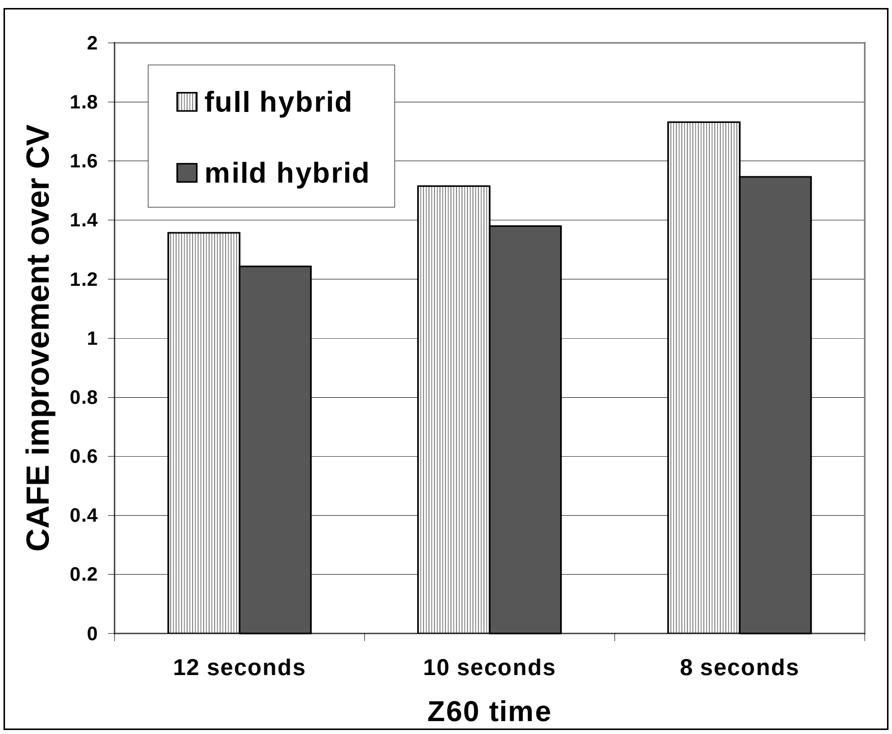



**Figure 4-4a Hybrid Vehicles' Fuel Economy Improvement over CVs as a Function of Acceleration Times (year 2010 ULS parallel HEV)**

It is important to avoid overgeneralizing this conclusion. Hybrids do not perform identically to CVs. In particular, as shown in Figure 4-4b, grid-independent hybrids will suffer in long-duration gradeability, because over time their batteries cannot sustain speeds on steep grades that CV drivetrains can easily sustain. The same holds true of towing capability – hybrids cannot tow as much weight as CVs with the same acceleration capability, because of their downsized engines. Thus, drivers concerned primarily with acceleration may view HEVs as plainly superior to CVs because of their large fuel economy boost; drivers with wider needs who are buying more power for towing or other reasons aside from acceleration capability might not be interested in hybrids despite their fuel economy advantage.

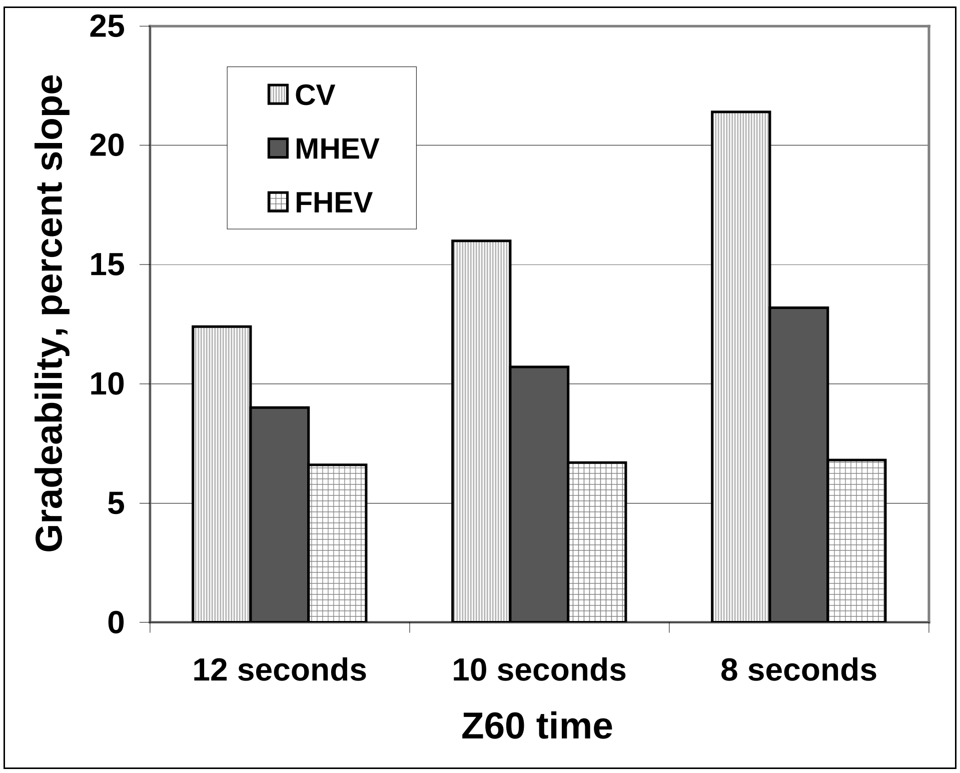



**Figure 4-4b CV and HEV Gradeability at 55 mph, Grid-Independent Parallel Hybrids**

4. **Parallel hybrids are cheaper than series.**

Figure 4-5 compares the projected sales prices of a year 2010 ULS CV with comparably-performing[55] (10-second Z60 time) HEVs.

---

[55] However, as discussed above, the hybrids will have less gradeability and towing capacity than CVs with the same acceleration capability.

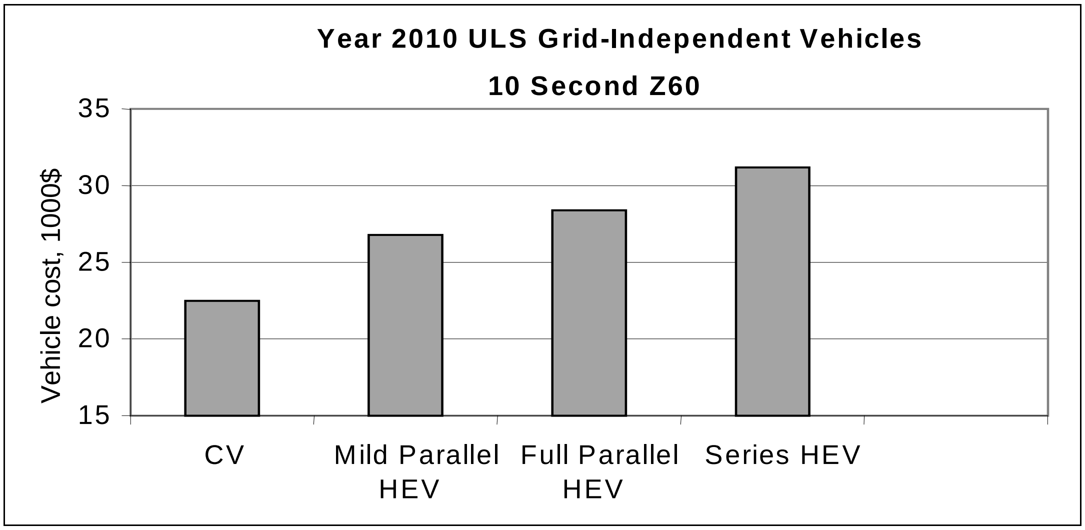



**Figure 4-5 Projected Year 2010 Cost of CVs and Hybrids**

Without sharper-than-expected decreases in the cost of electrical system components, hybrid vehicles will be more expensive than CVs, and series hybrids will be more expensive than comparable parallel hybrids. This is because the hybrids' cost savings from their smaller engines and transmissions (and, for the series hybrid, elimination of a multi-gear transmission) do not fully offset the high costs of the hybrids' motor/controller and battery. As shown in Table 4-5, the series hybrid actually has a larger engine than a comparable parallel (full) hybrid (though no transmission) and requires a much larger motor/controller, virtually assuring (with our price expectations) that it will be more expensive than the parallel hybrid.

**Table 4-5 Component Power Requirements of HEV Drivetrains (10-second Z60, year 2010 ULS vehicles)**

| | mild parallel | full parallel | series |
|---|---|---|---|
| Motor Size, kW | 22 | 43 | 87 |
| Engine, kW | 65 | 46 | 54 |
| Battery, kW | 25 | 49 | 46 |

5. **Demanding better acceleration performance is expensive.**

Figure 4-6 shows how vehicle sales price varies with acceleration.

The cost model results show that obtaining better acceleration performance is expensive for all vehicles, but especially so for hybrids. For the case shown, moving from 12-second Z60 to 8 seconds costs $3,900 for a CV but $7,200 for a parallel full hybrid and $5,700 for a series hybrid. The high cost of performance for a full parallel hybrid led us to examine the mild hybrid, because it became apparent that vehicle designers aiming at higher performance would have to trade off fuel economy performance and cost. Because the mild hybrid obtains increased performance by increasing both engine and motor/battery power, it can obtain this performance less expensively than a full hybrid, which increases only motor/battery power (because an engine kW is less expensive than a motor/battery kW).

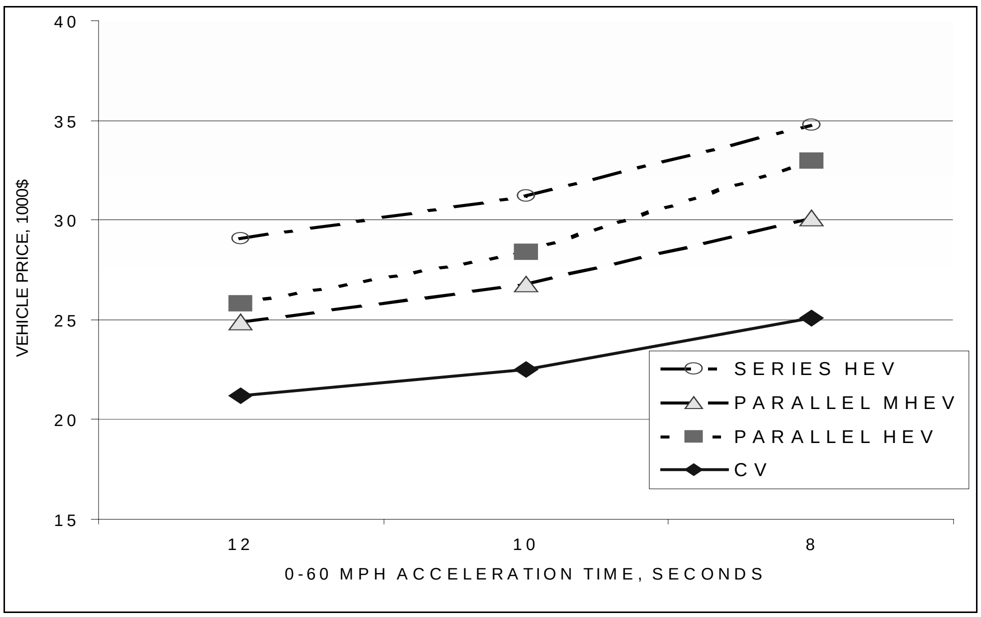



**Figure 4-6 Vehicle Cost as a Function of Acceleration Requirements (2010 ULS grid-independent vehicles)**

6. **HEV life cycle costs are extremely sensitive to assumptions but appear likely to exceed CV life cycle costs unless fuel prices rise to well over today's levels.**

As shown in Appendix A, under our baseline assumptions, life cycle costs for full HEVs exceed those of competing CVs in all cases. Because fuel costs are a modest proportion of total life cycle costs, it would take a large increase in gasoline price to create an incentive (equal life cycle costs for HEVs and CVs) to purchase HEVs. Figure 4-7 shows the "breakeven" gasoline prices (prices at which life cycle costs for the two vehicles would be equal) for CVs and parallel grid-independent ultralight steel hybrids with batteries that last the vehicle lifetime, at three performance levels (Z60 times of 8, 10, and 12 seconds). Parallel grid-independent hybrids have the lowest life cycle costs of the full hybrids evaluated thus far. The higher performance HEVs

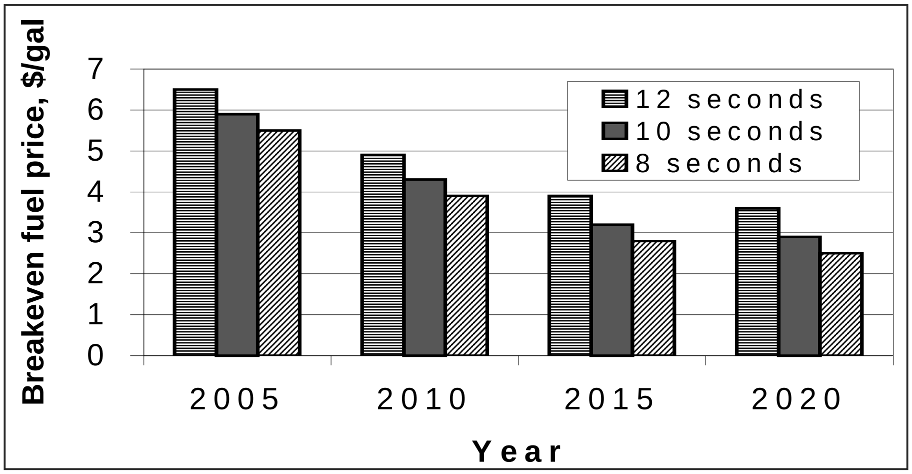



**Figure 4-7 Breakeven Fuel Prices for CVs and Parallel Grid-Independent Full Hybrids, for Three Performance Levels**

are more cost-effective, relative to their competing CVs, than the lesser performers, so their breakeven gasoline prices are lower – but still high in comparison to today's gasoline prices. Although the difference in purchase price between the HEV and CV grows considerably in moving toward higher performance, this is more than offset by growth in the HEV's fuel savings over the CV.

The breakeven gasoline prices get considerably lower over time, primarily because the cost of the hybrid's electrical components are presumed to drop considerably during this time period due to the effects of higher production (economies of scale) and learning.

As noted, the values in Figure 4-7 are based in part on the assumption that continuing battery development and the use of control strategies that maximize battery life will eliminate the need to replace the battery during the vehicle lifetime. Failure to reach this goal will increase life cycle costs significantly. For example, one battery replacement during the lifetime of the 12-second full hybrid above increases the breakeven gasoline price by about $0.50/gal in 2005 and $0.20/gal in 2020.

Figure 4-8 examines breakeven costs for "mild" variants of the parallel grid-independent hybrid. The mild hybrids have somewhat lower purchase costs than the full hybrids and pay a moderate penalty in fuel economy. The 12-second vehicles are slightly less cost-effective than the full hybrids; the faster, more expensive 10- and 8-second vehicles have superior cost-effectiveness. By 2015, the 8-second Z60 mild hybrid's breakeven fuel costs dip well below $2/gallon. Although $2/gallon is considerably higher than the 2015 gasoline price projected by the Energy Information Administration (EIA) Annual Energy Outlook, it appears a plausible price in the context of recent oil price fluctuations. In other words, it appears possible that these hybrids may be cost-effective in the 2015-2020 time frame, if their modeled fuel economy advantage and life cycle costs prove correct.

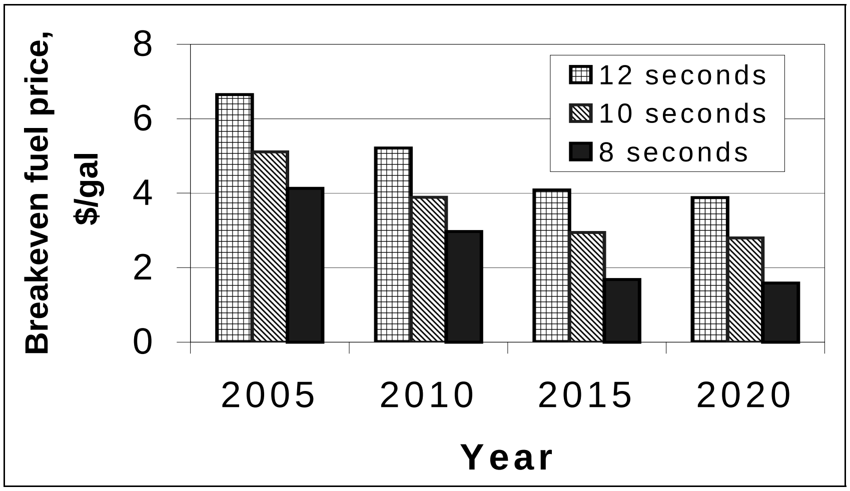



**Figure 4-8 Breakeven Fuel Prices for CVs and Parallel Grid-Independent Mild Hybrids, for Three Performance Levels**

7. **Grid-connected HEVs can achieve large reductions in oil, and significant reductions in total energy use and greenhouse emissions, in comparison to CVs, but at very high purchase and life cycle cost.**

Grid-connected HEVs are attractive conceptually because they are capable of operating part-time as EVs and can "refuel" a portion of their travel from the electrical grid, which offers significant air quality benefits as well as the potential to capture large savings in oil use and overall energy use. Figure 4-9 compares the total vehicle energy cost/mile of comparable parallel grid-connected and grid-independent HEVs and CVs (with the grid-connected HEVs, HEVGrid in the figure, presumed to travel a daily distance equal to 60% of their EV range on the FTP with grid-recharge and the remainder on the CAFE cycle, and the CVs and grid-independent HEVs traveling 100% of their miles on the CAFE cycle). Two CVs and two grid-independent HEVs are portrayed because it is not clear which offers the best comparison to the grid-connected vehicle. The CV8 and FHEV8 vehicles (attaining 8-second Z60 times) match the HEVGrid's hybrid-mode (combined engine/electric motor operation) acceleration capability, and the CV12 and full HEV (FHEV) 12 match the HEVGrid's EV-mode acceleration capability. The HEVGrid energy cost is only about half of the CV12's energy cost and a still smaller fraction of the CV8's energy cost, partly because it is more efficient in hybrid operation and partly because it is much more efficient in EV operation. However, neither of the grid-independent FHEVs have substantially higher energy costs than the HEVGrid, primarily because the heavier HEVGrid is less efficient in ordinary hybrid operations than either of the grid-independent HEVs, and the HEVGrid's less expensive all-electric operation is not so much less expensive than the FHEVs' gasoline operation that it lowers the total energy costs all that much.

As shown in Figures 4-10 and 4-11, both the initial purchase price and the life cycle costs of the grid-connected HEVs are much higher than that of the CVs, which is not surprising because the HEVGrids require substantially larger batteries and motor/controllers than grid-independent HEVs – the battery to provide the range and power needed to operate in EV mode, and the motor/controller to provide enough power to attain the required 12-second Z60 time. However,

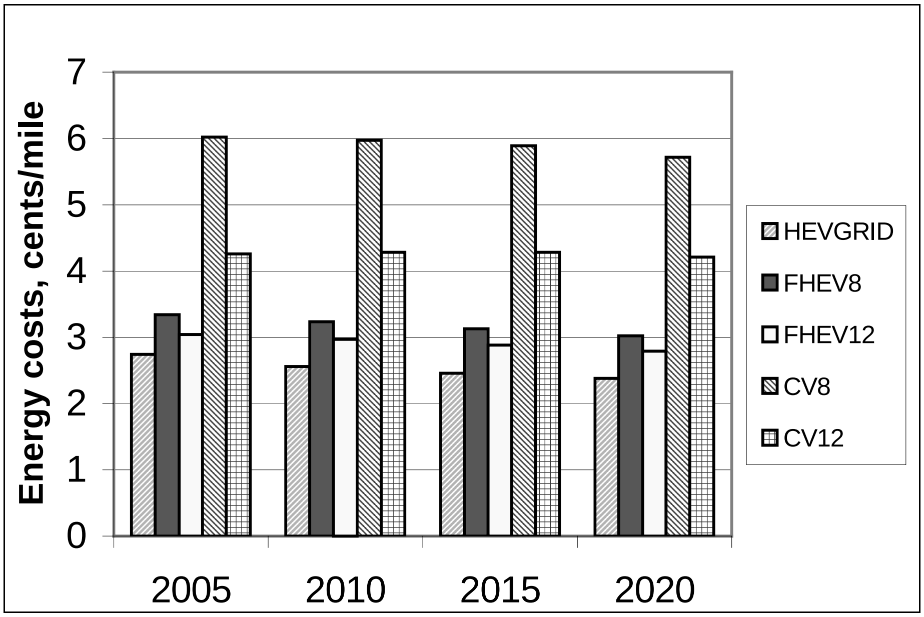



**Figure 4-9 Fuel + Electricity Cost: CVs vs. Parallel Grid-Connected (EV Z60 = 12 seconds) and Grid-Independent HEVs**

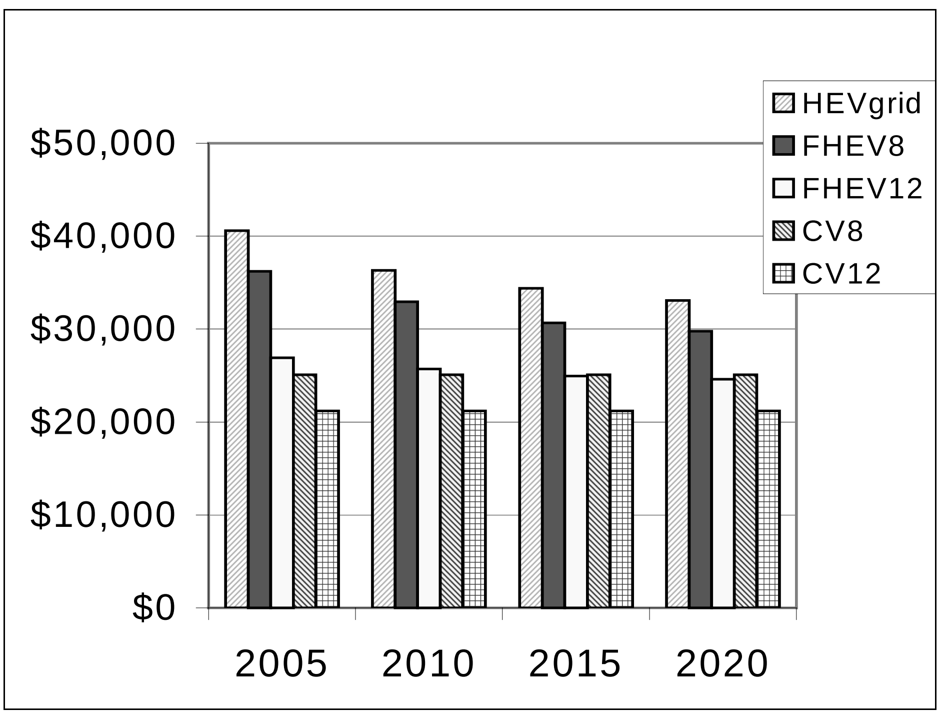



**Figure 4-10 Vehicle Cost Comparison: Grid-Connected and Grid-Independent Parallel HEVs vs. CV**

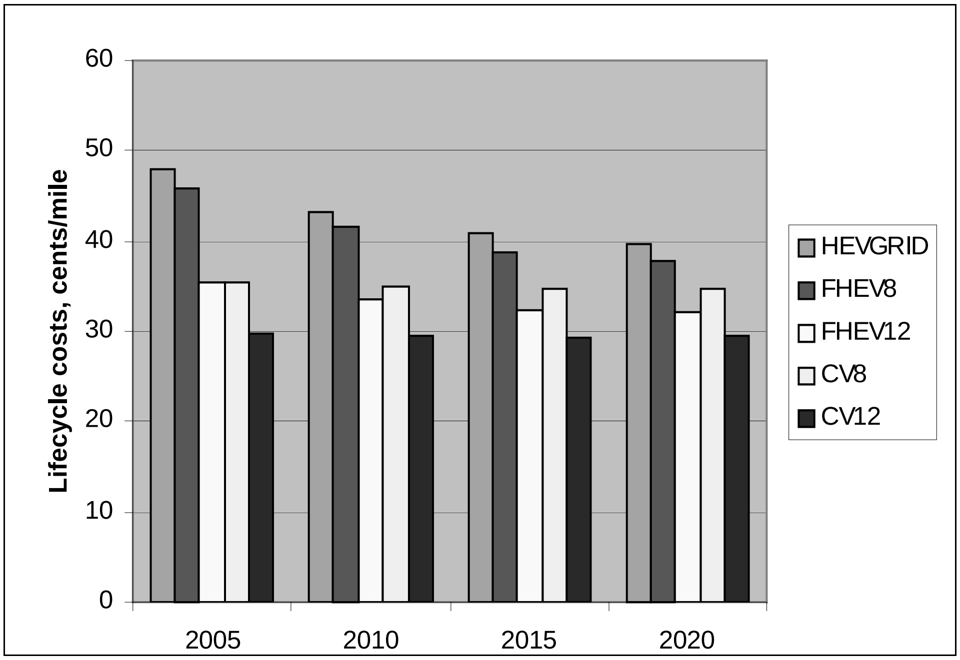



**Figure 4-11 Life Cycle Costs: CVs vs. Grid-Connected and Grid-Independent Parallel HEVs**

the 8-second Z60 grid-independent hybrid (FHEV8) costs almost as much as the HEVGrid and has life cycle costs nearly as high.

Figure 4-12 compares the gasoline use of "performance-equivalent" CVs, grid-independent parallel HEVs,[56] and grid-connected parallel HEVs in average long-term operation (that is, assuming that the grid-connected HEV operates part-time in all-electric mode and recharges its batteries overnight) in urban driving. Because the grid-connected HEV recharges a substantial portion of its miles from the grid, with virtually all grid electricity from nonpetroleum sources, it uses only about 1/3 as much gasoline as the CV and a bit more than half as much as the grid-independent HEV.

Finally, Figure 4-13 compares the fuel-cycle greenhouse emissions of "performance-equivalent" CVs and (parallel) grid-independent and grid-connected HEVs.[57]

---

56 All five vehicles have the same 0-60 mph time (8 seconds) when their engines are operating (e.g., the HEVGrid is in hybrid mode); the grid-connected HEV attains a 12-second 0-60 mph time in EV mode.

57 Assumptions: national average grid electricity, low sulfur reformulated gasoline (RFG) with no oxygenates, half of the grid-connected hybrid's miles are grid-recharged (based on about 13,000 miles/yr, 32.6 mile all-electric range calculated by ADVISOR run), 194,803 $gCO_2/10^6$ Btu electricity (from Table B48, Vol 3, GM 2001); gasoline well-to-tank emissions of 21,619 $gCO_2/10^6$ Btu (Table B5, Vol 3, GM 2001); gasoline combustion emissions of 98,096 $gCO_2/10^6$ Btu and energy content of 115,500 Btu/gallon (from GREET 1.6 spreadsheet).

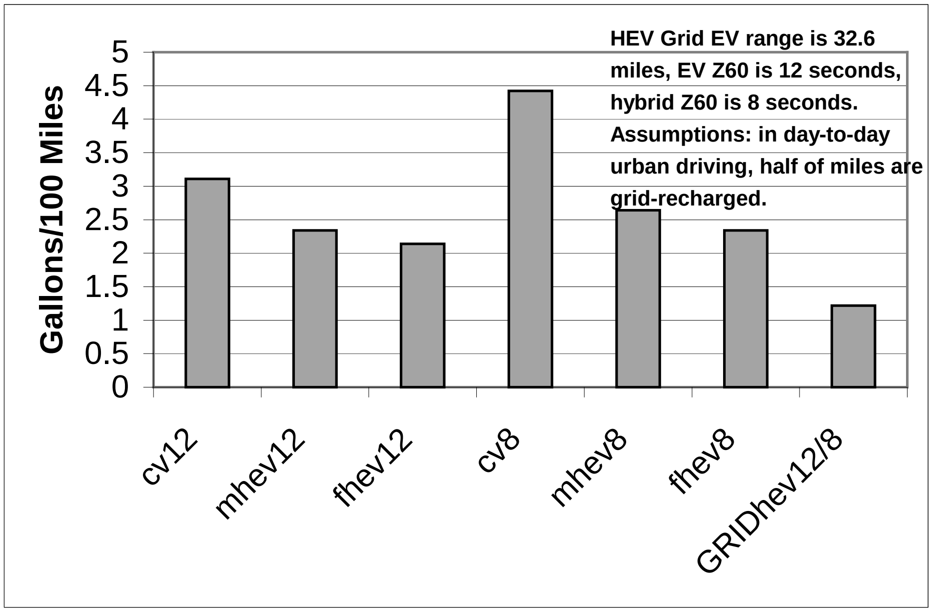



**Figure 4-12 Comparison of Gasoline Use: CV vs. Grid-Independent and Grid-Connected (32.6-mile range) HEVs in Urban Driving**

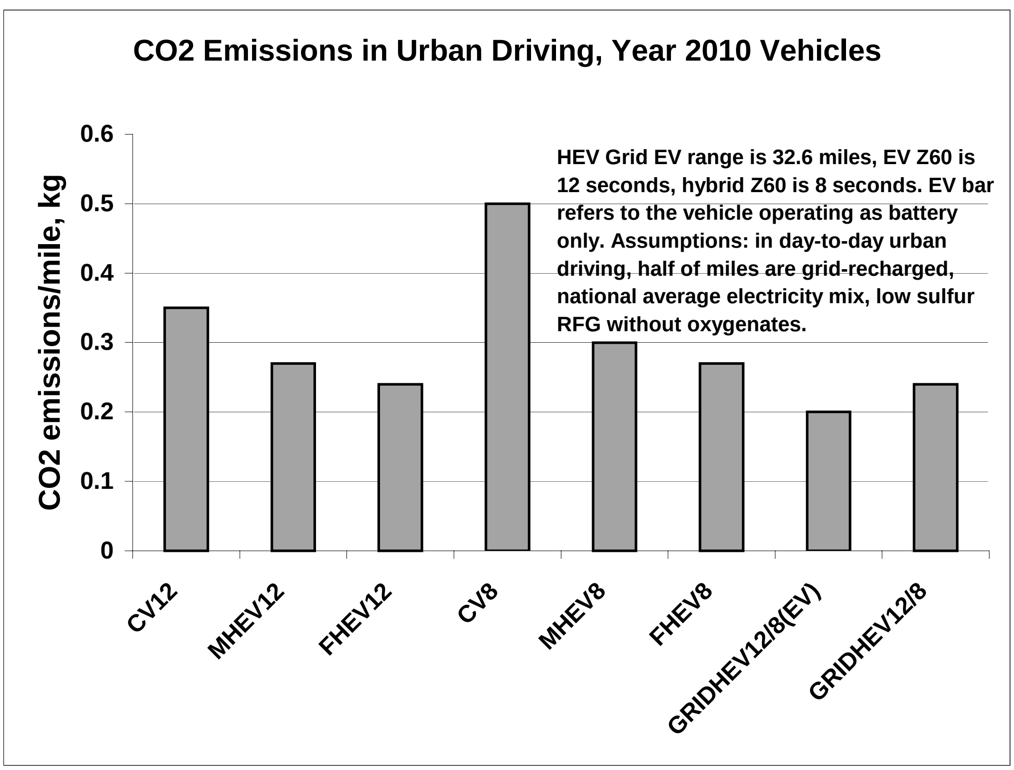



**Figure 4-13 $CO_2$ Emissions from Similar Conventional and Hybrid Vehicles in Urban Driving (FTP driving cycle, kilograms per mile)**

The grid-connected HEV offers a moderate reduction in greenhouse emissions over the grid-independent hybrids for this case, with the one exception being the 12-second Z60 full HEV; in the latter comparison, the HEV's Grid advantage in all-electric operation (next to the last column in the figure) is neutralized by a disadvantage in hybrid operation (because the heavier battery and motor required by the grid-connection reduce overall efficiency). The key question here is whether the 12-second FHEV represents a fair comparison to the Grid HEV, which matches the FHEV's performance when operating all-electrically but far exceeds it in hybrid operation.

These results are particularly sensitive to the type of recharge electricity assumed and the hybrid-mode SOC operating range of the battery. Graham et al. (2001) assert that battery longevity will not suffer unduly by operating the battery within a low SOC range, offering more rechargeable miles than assumed here, and a greater advantage in greenhouse emissions for the HEV Grid (note the next-to-the-last column in the figure, which shows the rate of greenhouse emissions when the vehicle is operating electrically). Also, the national average electricity assumed here is fairly heavily weighted toward coal; if grid recharge were weighted toward natural gas combined cycle plants or toward renewables, the greenhouse gases associated with the grid recharge would be considerably less than assumed here. For a thorough analysis of possible attributes of grid-connected HEVs, including cost, oil use, electricity use, emissions, and marketability, see Graham et al. (2001).

8. **Long-run (i.e., 2020) incremental prices of the parallel HEVs examined in this study vary from a 12% increment to a 32% increment, increasing as one proceeds from a mild hybrid to a full hybrid to a grid-connected hybrid. The estimates for parallel hybrids range from 12 to 14% for the three MHEV cases, from 16 to 19% for the FHEV cases, and from 25 to 32% for the HEVGrids with all-electric range from 23 to 33 miles.**

The percentage increase estimates in this study may be compared to those developed in the recent study by Weiss et al. (2001), done at MIT, and by Graham et al. (2001), under EPRI management. The one comparable case from the MIT study is an MHEV. The estimated increase in price is 9%, less than estimated in this study. The base method price increases from the EPRI study for the two FHEV cases examined are 20 and 21%. Though published earlier, the price estimates in the EPRI study were completed later than for this study. ANL's HEV cost estimation team worked with the EPRI study group to generate price increase estimates that reflect revised electric drive costs from those in this study. More optimism about component characteristics was included. The "ANL method" price increase estimates for the two EPRI FHEV cases were 12 and 13%, well below the 16 to 19% estimated here. The largest difference resulted from more optimism concerning battery costs. The EPRI base method price increase estimates for the hybrid with about 20 miles of all-electric range was 32% – at the top end of this study's estimate of 25 to 32%. The revised "ANL method" gave 21% for this EPRI case.

Compared to the one MHEV case in the MIT study, this study's MHEV price increase estimates are a bit higher. Compared to the two comparable FHEV and one comparable HEVGrid cases from the EPRI study, the estimates in this study are a bit lower. The revisions of the ANL method initiated in this study, and included in the EPRI study, are more optimistic than this study's estimates. A significant part of the difference arose from observation of rapid improvement of components used in marketed hybrids. This rapid improvement, occurring over less than two years, suggests that this study may be unduly pessimistic, at least about the rate of cost reduction that is possible for hybrid vehicle components.

The key hybrid components – battery (or other storage device), electric motor, and controller – are all under continuing development. DOE has established aggressive goals to reduce energy storage costs to levels well below those used in this study. Potential exists to substantially reduce motor and power electronics costs as well. Although the probability of achieving very high levels of cost reduction is not clear, success would significantly improve hybrids' cost-effectiveness and their prospects for mass market penetration.

## 4.7 References


An, F., F. Stodolsky, and D. Santini, 1999, *Hybrid Options for Light-Duty Vehicles*, SAE Technical Paper 1999-01-2929.

An, F., et al., 2000, *Scenario Analysis of Hybrid Class 3-7 Heavy Vehicles,* SAE Technical Paper 2000-01-0989, March.

Austin, T.C., F.J. DiGenova, J.M. Lee, and M. Carlock, 1992, *An Analysis of Driving Patterns in Los Angeles During 1992*, paper presented at CRC-APRAC On-Road Vehicle Emissions Workshop, Dec. 3.

Effa, R., and L.C. Larsen, 1993, *Development of Real-World Driving Cycles for Estimating Facility-Specific Emissions from Light-Duty Vehicles*, paper presented at the Air and Waste Management Specialty Conference on the Emission Inventory - Perception and Reality, Pasadena, Calif., Oct. 18-20.

Enns, P., J. German, and J. Markey, 1995, *EPA's Survey of In-Use Driving Patterns: Implications for Mobile Source Emission Inventories*, U.S. EPA, Office of Mobile Sources, Certification Division, Ann Arbor, Mich.

EPA, 1993, *Federal Test Procedure Review Project: Preliminary Technical Report*, U.S. Environmental Protection Agency, Office of Mobile Sources, Certification Division, Ann Arbor, Mich., May.

EPA, 1995, *Proposed Regulations for Revisions to the Federal Test Procedure for Emissions from Motor Vehicles; Proposed Rule*, *Federal Register*, Vol. 60, No. 25, pp. 7404-7424, Feb. 7.

Graham et al., 2001, *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options*, 1000349, Electric Power Research Institute, Palo Alto, Calif., July.

GM et al., 2001, General Motors Corporation, Argonne National Laboratory, *Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems – North American Analysis*, June.

Heavenrich, R.M., and K.H. Hellman, 1999, *Light-Duty Automotive Technology and Fuel Economy Trends through 1999*, U.S. Environmental Protection Agency EPA420-R-99-018, Sept.

Johnson, V.H., K.B. Wipke, and D.J. Rausen, 2000, *HEV Control Strategy for Real-Time Optimization of Fuel Economy and Emissions*, Society of Automotive Engineers OOFCC-67.

Newman, P.G., and J.R. Kenworthy, 1989, *Cities and Automobile Dependence: A Sourcebook,* Hants, England: Gower Publishing Co.

OTA, 1995, *Advanced Automotive Technology: Visions of a Super-Efficient Family Car*, United States Congress, Office of Technology Assessment Report OTA-ETT-638, Washington, D.C.

Santini, D.J., and A.D. Vyas, 1999, *Commercial Viability of Hybrid Vehicles: Best Household Use and Cross National Considerations*, USAEE/IAEE 20th Annual North American Conference, Aug. 20-Sept. 1.

Weiss et al., 2000, *On the Road in 2020: A Life-Cycle Analysis of New Automobile Technologies*, Energy Laboratory Report #MIT EL 00-003, Massachusetts Institute of Technology, Energy Laboratory, Cambridge, Mass., Oct.

# Section 4 Appendix A
# Table of Results: HEV Cost and ADVISOR Modeling, 11/1999-3/2000

**Performance and fuel economy data for CV, "mild" HEV, and "full" HEV**

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Design targets | | | | | | | | | |
| 0 to 60 time, 0.2 starting SOC | 12 sec | 12 sec | 12 sec | 10 sec | 10 sec | 10 sec | 8 sec | 8 sec | 8 sec |
| 55 mph gradeability | "float" | "float" | 6.50% | "float" | "float" | 6.50% | "float" | "float" | 6.50% |
| Vehicle type | convent-ional (CV) | "mild" HEV mid-sz.apu parallel grid indep. | "full" HEV parallel grid indep. | convent-ional (CV) | "mild" HEV mid-sz.apu parallel grid indep. | "full" HEV parallel grid indep. | convent-ional (CV) | "mild" HEV mid-sz.apu parallel grid indep. | "full" HEV parallel grid indep. |
| Vehicle attributes | | | | | | | | | |
| Cd, Crr, frontal area | notes | notes | notes | notes | notes | notes | notes | notes | notes |
| empty mass (kg) | 1175 | 1246 | 1247 | 1248 | 1321 | 1328 | 1366 | 1453 | 1466 |
| body material (notes) | uls | uls | uls | uls | uls | uls | uls | uls | uls |
| APU (kW) (notes) | 66 | 55 | 44 | 85 | 65 | 46 | 116 | 82 | 49 |
| battery(@20%soc) kW | n/a | 16 | 28 | n/a | 25 | 49 | n/a | 43 | 85 |
| motor - peak kW | n/a | 14 | 25 | n/a | 22 | 43 | n/a | 39 | 75 |
| motor - cont. kW | n/a | 10 | 17 | n/a | 15 | 30 | n/a | 27 | 51 |
| Hevcost 0-60 time (soc) | 12 | 12 | 12 | 10 | 10 | 10 | 8 | 8 | 8 |
| Hevcost 55 mph gradeability | N/E | N/E | 6.5% | N/E | N/E | 6.5% | N/E | N/E | 6.5% |
| Advisor (A2.1.1) results (notes) | | | | | | | | | |
| 55 mph gradeability | 12.4% | 9.0% | 6.6% | 16.0% | 10.7% | 6.7% | 21.4% | 13.2% | 6.8% |
| 0-60 time (initial soc) | 12 sec | 12.2 sec (0.2) | 12 sec (0.2) | 9.9 sec | 10 sec (0.2) | 9.8 sec (0.2) | 8.1 sec | 8.1 sec (0.2) | 8 sec (0.2) |
| Advisor (A2.1.1) fuel economy results ( mpg) (SOC max/min=.7/.6 - notes) | | | | | | | | | |
| Driving Cycle | | | | | | | | | |
| NYCC | 15.7 | 24.4 | 26.7 | 13.3 | 23.6 | 26.2 | 10.6 | 21.9 | 24.6 |
| Japan 1015 | 28.1 | 47.1 | 50.7 | 24.0 | 45.7 | 48.6 | 19.3 | 41.3 | 46.1 |
| FTP cycle (city) | 32.2 | 42.7 | 46.7 | 27.7 | 41.3 | 45.2 | 22.6 | 37.9 | 42.5 |
| CAFÉ | 37.5 | 46.6 | 50.9 | 32.6 | 45.0 | 49.4 | 26.9 | 41.6 | 46.6 |
| US06 | 33.1 | 35.2 | 38.3 | 30.2 | 35.1 | 38.5 | 26.4 | 34.7 | 37.4 |
| Hwy | 47.1 | 52.4 | 57 | 41.6 | 50.4 | 55.7 | 35.0 | 47.2 | 52.8 |
| REP5 | 38.0 | 40.3 | 44 | 34.3 | 39.9 | 43.8 | 29.6 | 38.6 | 41.7 |
| A2 run date: | 11/24/99 | 11/24/99 | 11/24/99 | 11/24/99 | 11/24/99 | 11/24/99 | 11/28/99 | 11/28/99 | 11/28/99 |

Notes:
- For all vehicles : Cd = 0.26, Crr = 0.0075, frontal area = 2.06 sq.m
- For all vehicles : 5-speed manual transmission (gears of 3.45, 1.94, 1.29, 0.97, 0.75 ; axle of 3.89)
- ULSs = ultralight steel; al (not applicable here) = aluminum
- APU for "mild hybrids" is halfway between CV and full HEV APU sizes
- HEV ADVISOR accel. & grade runs made at initial SOC = 0.2
- HEV ADVISOR mpg runs made for SOC range 0.7 to 0.6 .B93
- mass, APU, battery, and motor specified by HEVCOST, but after iterations to match with ADVISOR. Both ADVISOR and HEVCOST were modified repeatedly until they matched empirical data, as discussed in text.
- ADVISOR version used was A2.1.1 (of 13 Apr99). Current versions may not produce identical results.

**Performance and fuel economy data for various parallel and series**

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Design targets | | | | | | | | | |
| 0 to 60 mph time(sec) | float | float | float | 12 | 10 | 8 | 12 | 12 | 12 |
| grade (%) | float | float | float | 6.5 | 6.5 | 6.5 | 6.5 | 6.5 | 6.5 |
| EV range (mi) | 23.2 | 26.3 | 30.5 | n/a | n/a | n/a | 21.1 | 24.0 | 28.2 |
| All electric 0-60 time (sec) | 16.0 | 14.0 | 12.0 | n/a | n/a | n/a | 16.0 | 14.0 | 12.0 |
| Vehicle type | parallel grid connected | parallel grid connected | parallel grid connected | series grid indep. | series grid indep. | series grid indep. | series grid connected | series grid connected | series grid connected |
| Vehicle attributes | | | | | | | | | |
| Cd, Crr, frontal area | notes | notes | notes | notes | notes | notes | notes | notes | notes |
| empty mass (kg) | 1439 | 1491 | 1566 | 1341 | 1404 | 1513 | 1468 | 1504 | 1559 |
| APU (kW) | 48 | 49 | 50 | 52 | 54 | 56 | 56 | 57 | 59 |
| battery(@20%soc) kW | 62 | 73 | 89 | 30 | 46 | 75 | 60 | 70 | 85 |
| | interm.power | interm.power | interm.power | high power | high power | high power | interm.power | interm.power | interm.power |
| motor - peak kW | 54 | 64 | 78 | 71 | 87 | 115 | 70 | 72 | 75 |
| motor - cont. kW | 37 | 44 | 53 | 49 | 60 | 79 | 48 | 49 | 51 |
| Advisor (A2.1.1) results | | | | | | | | | |
| grade (%) | 6.7 | 6.7 | 6.6 | 6.9 | 7 | 6.9 | 7 | 7.1 | 7.2 |
| Z60 time (init. soc) | 9.1 (0.2) | 8.6 (0.2) | 8.1 (0.2) | 11.8 (0.2) | 9.7 (0.2) | 7.9 (0.2) | 12.3 (0.2) | 12.2 (0.2) | 12.1 (0.2) |
| all EL Z60 time (init. soc) | 15.9 (0.30) | 13.7 (0.30) | 12.0 (0.30) | n/a | n/a | n/a | 15.6 (0.30) | 13.6 (0.30) | 12.2 (0.30) |
| all EL Z60 time (init. soc) | 15.9 (0.25) | 13.7 (0.25) | 12.0 (0.25) | | | | 16.2 (0.25) | 14.0 (0.25) | 12.3 (0.25) |
| all EL Z60 time (init. soc) | 16.1 (0.20) | 13.9 (0.20) | 12.0 (0.20) | | | | 17.4 (0.20) | 15.0 (0.20) | 12.7 (0.20) |
| all EL range (miles) (SOC max/min=.95/.2) | 23.2 | 27 | 32.6 | n/a | n/a | n/a | 21.1 | 24.2 | 29.9 |
| A2 run date: | 12/15/99 | 12/15/99 | 12/15/99 | | | | 12/15/99 | 12/15/99 | 12/15/99 |
| Advisor (A2.1.1) fuel economy results (SOC max/min=.7/.6) | | | | | | | | | |
| Driving Cycle | | | | | | | | | |
| NYCC | 25.3 | 24.2 | 23.7 | 23.0 | 23.8 | 23.2 | 24.6 | 24.9 | 22.8 |
| Japan 1015 | 46.4 | 45.2 | 44.1 | 40.7 | 39.7 | 37.4 | 38.7 | 38.8 | 34.0 |
| FTP cycle (city) | 43.3 | 42.2 | 41 | 38.8 | 38.1 | 37.0 | 38.7 | 39.1 | 38.2 |
| CAFÉ | 47.5 | 46.4 | 45.1 | 43.9 | 42.9 | 41.5 | 43.2 | 43.3 | 42.2 |
| US06 | 37.7 | 36.9 | 36.2 | 31.1 | 31.2 | 31.9 | 32.0 | 31.8 | 31.7 |
| Hwy | 53.8 | 52.8 | 51.5 | 52.2 | 50.9 | 48.5 | 50.5 | 50.0 | 48.2 |
| REP5 | 42.2 | 41.5 | 40.8 | 38.2 | 37.5 | 36.6 | 36.9 | 37.1 | 36.6 |
| | pDD | pEE | pFF | sGG | sHH | sII | sJJ | sKK | sLL |
| A2 run date: | 12/10/99 | 12/10/99 | 12/10/99 | 11/30/99 | 12/1/99 | 12/1/99 | 12/10/99 | 12/10/99 | 12/10/99 |

Notes:
- For all vehicles : Cd = 0.26, Crr = 0.0075, frontal area = 2.06 sq.m
- For all vehicles : 5-spd manual trans. (gears of 3.45, 1.94, 1.29, 0.97, 0.75 ; axle of 3.89)
- HEV ADVISOR accel. & grade runs made at initial SOC = 0.2
- HEV ADVISOR mpg runs made for SOC range 0.7 to 0.6
- all electric (EL) Z60 and range for vehicle with APU = 0 kW.
- all electric range made for SOC range 0.95 to 0.20
- mass, APU, battery, and motor specified by HEVCOST
- ADVISOR version is A2.1.1 (of 13 Apr99)
- grid connected vehicles use intermediate power battery (350W/kg, 52Wh/kg at 20% soc)
- grid independent vehicles use high power battery (520W/kg, 46Wh/kg at 20% soc)

**Argonne National Laboratory: Center for Transportation Research**
**A Methodology for Projecting Parallel Hybrid Electric Vehicle Cost**
**(All costs are in 1995 dollars. Battery costs estimated for the HEVTECA project.)**

**HEVTECA (Parallel, Grid-independent, UL Steel, HP Batt, 8-12s Z60 Time, APU for 6.5% Grade): ADVISOR-2 Components Matching**

| | Vehicle type: **Midsize Car**<br>Z60 Time: **12 seconds**<br>Battery type: **NiMH (High Power)** | | | | Vehicle type: **Midsize Car**<br>Z60 Time: **10 seconds**<br>Battery type: **NiMH (High Power)** | | | | Vehicle type: **Midsize Car**<br>Z60 Time: **8 seconds**<br>Battery type: **NiMH (High Power)** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Item** | **2005** | **2010** | **2015** | **2020** | **2005** | **2010** | **2015** | **2020** | **2005** | **2010** | **2015** | **2020** |
| | **Purchase Price** | | | | **Purchase Price** | | | | **Purchase Price** | | | |
| **Conventional Vehicle** | $ 21,200 | $ 21,200 | $ 21,200 | $ 21,200 | $ 22,500 | $ 22,500 | $ 22,500 | $ 22,500 | $ 25,100 | $ 25,100 | $ 25,100 | $ 25,100 |
| **Hybrid Electric Vehicle** | | | | | | | | | | | | |
| Common components | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 |
| Additional aluminum cost | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - |
| Auxiliary Power Unit | $ 2,940 | $ 2,980 | $ 2,970 | $ 3,070 | $ 3,030 | $ 3,080 | $ 3,030 | $ 3,120 | $ 3,220 | $ 3,230 | $ 3,180 | $ 3,290 |
| Generator | $ 690 | $ 590 | $ 550 | $ 520 | $ 710 | $ 610 | $ 550 | $ 540 | $ 740 | $ 630 | $ 570 | $ 550 |
| Inverter & Power Electronics | $ 1,870 | $ 1,440 | $ 1,170 | $ 1,020 | $ 2,660 | $ 2,040 | $ 1,570 | $ 1,370 | $ 4,140 | $ 3,060 | $ 2,290 | $ 1,950 |
| Motor | $ 970 | $ 820 | $ 710 | $ 680 | $ 1,480 | $ 1,190 | $ 1,010 | $ 960 | $ 2,370 | $ 1,870 | $ 1,530 | $ 1,430 |
| Transmission | $ 900 | $ 860 | $ 800 | $ 790 | $ 1,130 | $ 1,060 | $ 980 | $ 970 | $ 1,520 | $ 1,420 | $ 1,310 | $ 1,280 |
| System control | $ 420 | $ 410 | $ 390 | $ 350 | $ 420 | $ 410 | $ 390 | $ 350 | $ 420 | $ 410 | $ 390 | $ 350 |
| Other body parts | $ 400 | $ 390 | $ 380 | $ 370 | $ 400 | $ 390 | $ 380 | $ 370 | $ 400 | $ 390 | $ 380 | $ 370 |
| Additional HVAC Cost | $ 120 | $ 110 | $ 110 | $ 110 | $ 120 | $ 110 | $ 110 | $ 110 | $ 120 | $ 110 | $ 110 | $ 110 |
| First Battery Price | $ 2,320 | $ 1,840 | $ 1,590 | $ 1,430 | $ 3,960 | $ 3,210 | $ 2,700 | $ 2,460 | $ 7,020 | $ 5,570 | $ 4,650 | $ 4,170 |
| Total HEV Price | $ 26,900 | $ 25,710 | $ 24,940 | $ 24,610 | $ 30,180 | $ 28,370 | $ 26,990 | $ 26,520 | $ 36,220 | $ 32,960 | $ 30,680 | $ 29,770 |
| | **Operating Cost** | | | | **Operating Cost** | | | | **Operating Cost** | | | |
| **Conventional Vehicle** | | | | | | | | | | | | |
| Fuel cost (c/mi) | 4.26 | 4.28 | 4.28 | 4.21 | 4.87 | 4.93 | 4.95 | 4.91 | 6.02 | 5.97 | 5.89 | 5.72 |
| Non-fuel cost (c/mi) | 4.90 | 4.97 | 5.05 | 5.20 | 4.90 | 4.97 | 5.05 | 5.20 | 4.90 | 4.97 | 5.05 | 5.20 |
| Total cost (c/mi) | 9.16 | 9.26 | 9.33 | 9.41 | 9.77 | 9.90 | 10.00 | 10.11 | 10.92 | 10.94 | 10.94 | 10.92 |
| **Hybrid Electric Vehicle** | | | | | | | | | | | | |
| Electricity cost (c/mi) | - | - | - | - | - | - | - | - | - | - | - | - |
| Fuel cost (c/mi) | 3.04 | 2.97 | 2.88 | 2.79 | 3.12 | 3.06 | 2.98 | 2.90 | 3.34 | 3.24 | 3.13 | 3.02 |
| Non-fuel cost (c/mi) | 5.55 | 5.63 | 5.72 | 5.89 | 5.55 | 5.63 | 5.72 | 5.89 | 5.55 | 5.63 | 5.72 | 5.89 |
| Battery cost (c/mi) | 2.81 | 2.11 | 1.76 | 1.60 | 4.80 | 3.69 | 2.99 | 2.76 | 8.51 | 6.40 | 5.16 | 4.67 |
| Total cost (c/mi) | 11.40 | 10.71 | 10.36 | 10.28 | 13.47 | 12.38 | 11.69 | 11.55 | 17.39 | 15.28 | 14.01 | 13.58 |
| | **Life-cycle Cost** | | | | **Life-cycle Cost** | | | | **Life-cycle Cost** | | | |
| **Conventional Vehicle** | | | | | | | | | | | | |
| Purchase Price (c/mi) | 20.80 | 20.50 | 20.20 | 20.20 | 22.08 | 21.75 | 21.44 | 21.44 | 24.63 | 24.27 | 23.91 | 23.91 |
| Operating Cost (c/mi) | 9.16 | 9.26 | 9.33 | 9.41 | 9.77 | 9.90 | 10.00 | 10.11 | 10.92 | 10.94 | 10.94 | 10.92 |
| Less Scrappage Value (c/mi) | (0.13) | (0.13) | (0.12) | (0.12) | (0.14) | (0.14) | (0.13) | (0.13) | (0.15) | (0.15) | (0.15) | (0.15) |
| Total Life-cycle Cost (c/mi) | 29.84 | 29.62 | 29.40 | 29.48 | 31.71 | 31.52 | 31.31 | 31.41 | 35.39 | 35.06 | 34.71 | 34.69 |
| **Hybrid Electric Vehicle** | | | | | | | | | | | | |
| Purchase Price - Battery (c/mi) | 24.12 | 23.08 | 22.25 | 22.09 | 25.73 | 24.32 | 23.14 | 22.92 | 28.65 | 26.48 | 24.80 | 24.39 |
| Operating Cost (c/mi) | 11.40 | 10.71 | 10.36 | 10.28 | 13.47 | 12.38 | 11.69 | 11.55 | 17.39 | 15.28 | 14.01 | 13.58 |
| Less Scrappage Value (c/mi) | (0.15) | (0.14) | (0.14) | (0.14) | (0.16) | (0.15) | (0.14) | (0.14) | (0.18) | (0.16) | (0.15) | (0.15) |
| Total Life-cycle Cost (c/mi) | 35.37 | 33.65 | 32.47 | 32.23 | 39.03 | 36.55 | 34.69 | 34.33 | 45.87 | 41.59 | 38.66 | 37.82 |
| | **Important HEV Parameters** | | | | **Important HEV Parameters** | | | | **Important HEV Parameters** | | | |
| Motor power (kW): Peak | 26 | 25 | 23 | 23 | 46 | 43 | 40 | 40 | 81 | 76 | 70 | 68 |
| Motor power (kW): Constant | 18 | 17 | 16 | 16 | 32 | 30 | 28 | 28 | 56 | 52 | 48 | 47 |
| APU power (kW) | 46 | 44 | 41 | 40 | 48 | 46 | 42 | 41 | 52 | 49 | 45 | 44 |
| Generator power (kW) | 15 | 14 | 14 | 13 | 16 | 15 | 14 | 14 | 17 | 16 | 15 | 15 |
| Battery power (kW) | 31 | 28 | 26 | 25 | 53 | 49 | 44 | 43 | 94 | 85 | 76 | 73 |
| Battery energy (kWh) | 2.7 | 2.5 | 2.3 | 2.2 | 4.6 | 4.4 | 3.9 | 3.7 | 8.2 | 7.6 | 6.7 | 6.3 |
| Battery mass (kg) | 62 | 54 | 48 | 44 | 106 | 94 | 81 | 75 | 188 | 164 | 139 | 127 |
| Total vehicle mass (kg) | 1,276 | 1,247 | 1,217 | 1,201 | 1,364 | 1,328 | 1,284 | 1,265 | 1,525 | 1,468 | 1,407 | 1,377 |
| Zero-to-60 mph time(s) | 12.0 | 12.0 | 12.0 | 12.0 | 10.0 | 10.0 | 10.0 | 10.0 | 8.0 | 8.0 | 8.0 | 8.0 |
| Estimated all-elec range (mi) | 7 | 7 | 6 | 7 | 12 | 11 | 11 | 11 | 19 | 19 | 18 | 18 |

Parallel Grid-independent FHV: HEVCOST Model Run with ADVISOR mpg (for CV & HEV) dated 11/28/99, PNGV p1& CV5 (with default gear ratio) runs .
The default battery life used, requires one battery replacement.
Run date: 3/30/2000

**Argonne National Laboratory: Center for Transportation Research**

**A Methodology for Projecting Parallel Hybrid Electric Vehicle Cost**

**(All costs are in 1995 dollars. Battery costs estimated for the HEVTECA project.)**

**HEVTECA (Parallel, Grid-independent, UL Steel, HP Batt thru HEV Life, 8-12s Z60 Time, APU for 6.5% Grade): ADVISOR-2 Components Matching**

| | Vehicle type: **Midsize Car** Z60 Time: **12 seconds** Battery type: **NiMH (High Power)** | | | | Vehicle type: **Midsize Car** Z60 Time: **10 seconds** Battery type: **NiMH (High Power)** | | | | Vehicle type: **Midsize Car** Z60 Time: **8 seconds** Battery type: **NiMH (High Power)** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Item** | **2005** | **2010** | **2015** | **2020** | **2005** | **2010** | **2015** | **2020** | **2005** | **2010** | **2015** | **2020** |
| | **Purchase Price** | | | | **Purchase Price** | | | | **Purchase Price** | | | |
| **Conventional Vehicle** | $ 21,200 | $ 21,200 | $ 21,200 | $ 21,200 | $ 22,500 | $ 22,500 | $ 22,500 | $ 22,500 | $ 25,100 | $ 25,100 | $ 25,100 | $ 25,100 |
| **Hybrid Electric Vehicle** | | | | | | | | | | | | |
| Common components | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 |
| Additional aluminum cost | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - |
| Auxiliary Power Unit | $ 2,940 | $ 2,980 | $ 2,970 | $ 3,070 | $ 3,030 | $ 3,080 | $ 3,030 | $ 3,120 | $ 3,220 | $ 3,230 | $ 3,180 | $ 3,290 |
| Generator | $ 690 | $ 590 | $ 550 | $ 520 | $ 710 | $ 610 | $ 550 | $ 540 | $ 740 | $ 630 | $ 570 | $ 550 |
| Inverter & Power Electronics | $ 1,870 | $ 1,440 | $ 1,170 | $ 1,020 | $ 2,660 | $ 2,040 | $ 1,570 | $ 1,370 | $ 4,140 | $ 3,060 | $ 2,290 | $ 1,950 |
| Motor | $ 970 | $ 820 | $ 710 | $ 680 | $ 1,480 | $ 1,190 | $ 1,010 | $ 960 | $ 2,370 | $ 1,870 | $ 1,530 | $ 1,430 |
| Transmission | $ 900 | $ 860 | $ 800 | $ 790 | $ 1,130 | $ 1,060 | $ 980 | $ 970 | $ 1,520 | $ 1,420 | $ 1,310 | $ 1,280 |
| System control | $ 420 | $ 410 | $ 390 | $ 350 | $ 420 | $ 410 | $ 390 | $ 350 | $ 420 | $ 410 | $ 390 | $ 350 |
| Other body parts | $ 400 | $ 390 | $ 380 | $ 370 | $ 400 | $ 390 | $ 380 | $ 370 | $ 400 | $ 390 | $ 380 | $ 370 |
| Additional HVAC Cost | $ 120 | $ 110 | $ 110 | $ 110 | $ 120 | $ 110 | $ 110 | $ 110 | $ 120 | $ 110 | $ 110 | $ 110 |
| First Battery Price | $ 2,320 | $ 1,840 | $ 1,590 | $ 1,430 | $ 3,960 | $ 3,210 | $ 2,700 | $ 2,460 | $ 7,020 | $ 5,570 | $ 4,650 | $ 4,170 |
| Total HEV Price | $ 26,900 | $ 25,710 | $ 24,940 | $ 24,610 | $ 30,180 | $ 28,370 | $ 26,990 | $ 26,520 | $ 36,220 | $ 32,960 | $ 30,680 | $ 29,770 |
| | **Operating Cost** | | | | **Operating Cost** | | | | **Operating Cost** | | | |
| **Conventional Vehicle** | | | | | | | | | | | | |
| Fuel cost (c/mi) | 4.26 | 4.28 | 4.28 | 4.21 | 4.87 | 4.93 | 4.95 | 4.91 | 6.02 | 5.97 | 5.89 | 5.72 |
| Non-fuel cost (c/mi) | 4.90 | 4.97 | 5.05 | 5.20 | 4.90 | 4.97 | 5.05 | 5.20 | 4.90 | 4.97 | 5.05 | 5.20 |
| Total cost (c/mi) | 9.16 | 9.26 | 9.33 | 9.41 | 9.77 | 9.90 | 10.00 | 10.11 | 10.92 | 10.94 | 10.94 | 10.92 |
| **Hybrid Electric Vehicle** | | | | | | | | | | | | |
| Electricity cost (c/mi) | - | - | - | - | - | - | - | - | - | - | - | - |
| Fuel cost (c/mi) | 3.04 | 2.97 | 2.88 | 2.79 | 3.12 | 3.06 | 2.98 | 2.90 | 3.34 | 3.24 | 3.13 | 3.02 |
| Non-fuel cost (c/mi) | 5.55 | 5.63 | 5.72 | 5.89 | 5.55 | 5.63 | 5.72 | 5.89 | 5.55 | 5.63 | 5.72 | 5.89 |
| Battery cost (c/mi) | 2.28 | 1.78 | 1.51 | 1.36 | 3.89 | 3.10 | 2.57 | 2.34 | 6.89 | 5.38 | 4.43 | 3.97 |
| Total cost (c/mi) | 10.87 | 10.38 | 10.12 | 10.04 | 12.55 | 11.80 | 11.27 | 11.14 | 15.78 | 14.26 | 13.28 | 12.88 |
| | **Life-cycle Cost** | | | | **Life-cycle Cost** | | | | **Life-cycle Cost** | | | |
| **Conventional Vehicle** | | | | | | | | | | | | |
| Purchase Price (c/mi) | 20.80 | 20.50 | 20.20 | 20.20 | 22.08 | 21.75 | 21.44 | 21.44 | 24.63 | 24.27 | 23.91 | 23.91 |
| Operating Cost (c/mi) | 9.16 | 9.26 | 9.33 | 9.41 | 9.77 | 9.90 | 10.00 | 10.11 | 10.92 | 10.94 | 10.94 | 10.92 |
| Less Scrappage Value (c/mi) | (0.13) | (0.13) | (0.12) | (0.12) | (0.14) | (0.14) | (0.13) | (0.13) | (0.15) | (0.15) | (0.15) | (0.15) |
| Total Life-cycle Cost (c/mi) | 29.84 | 29.62 | 29.40 | 29.48 | 31.71 | 31.52 | 31.31 | 31.41 | 35.39 | 35.06 | 34.71 | 34.69 |
| **Hybrid Electric Vehicle** | | | | | | | | | | | | |
| Purchase Price - Battery (c/mi) | 24.12 | 23.08 | 22.25 | 22.09 | 25.73 | 24.32 | 23.14 | 22.92 | 28.65 | 26.48 | 24.80 | 24.39 |
| Operating Cost (c/mi) | 10.87 | 10.38 | 10.12 | 10.04 | 12.55 | 11.80 | 11.27 | 11.14 | 15.78 | 14.26 | 13.28 | 12.88 |
| Less Scrappage Value (c/mi) | (0.15) | (0.14) | (0.14) | (0.14) | (0.16) | (0.15) | (0.14) | (0.14) | (0.18) | (0.16) | (0.15) | (0.15) |
| Total Life-cycle Cost (c/mi) | 34.84 | 33.31 | 32.23 | 31.99 | 38.12 | 35.97 | 34.27 | 33.92 | 44.25 | 40.58 | 37.93 | 37.12 |
| | **Important HEV Parameters** | | | | **Important HEV Parameters** | | | | **Important HEV Parameters** | | | |
| Motor power (kW): Peak | 26 | 25 | 23 | 23 | 46 | 43 | 40 | 40 | 81 | 76 | 70 | 68 |
| Motor power (kW): Constant | 18 | 17 | 16 | 16 | 32 | 30 | 28 | 28 | 56 | 52 | 48 | 47 |
| APU power (kW) | 46 | 44 | 41 | 40 | 48 | 46 | 42 | 41 | 52 | 49 | 45 | 44 |
| Generator power (kW) | 15 | 14 | 14 | 13 | 16 | 15 | 14 | 14 | 17 | 16 | 15 | 15 |
| Battery power (kW) | 31 | 28 | 26 | 25 | 53 | 49 | 44 | 43 | 94 | 85 | 76 | 73 |
| Battery energy (kWh) | 2.7 | 2.5 | 2.3 | 2.2 | 4.6 | 4.4 | 3.9 | 3.7 | 8.2 | 7.6 | 6.7 | 6.3 |
| Battery mass (kg) | 62 | 54 | 48 | 44 | 106 | 94 | 81 | 75 | 188 | 164 | 139 | 127 |
| Total vehicle mass (kg) | 1,276 | 1,247 | 1,217 | 1,201 | 1,364 | 1,328 | 1,284 | 1,265 | 1,525 | 1,468 | 1,407 | 1,377 |
| Zero-to-60 mph time(s) | 12.0 | 12.0 | 12.0 | 12.0 | 10.0 | 10.0 | 10.0 | 10.0 | 8.0 | 8.0 | 8.0 | 8.0 |
| Estimated all-elec range (mi) | 7 | 7 | 6 | 7 | 12 | 11 | 11 | 11 | 19 | 19 | 18 | 18 |

Parallel Grid-independent FHV: HEVCOST Model Run with ADVISOR mpg (for CV & HEV) dated 11/28/99, PNGV p1& CV5 (with default gear ratio) runs .

The battery life increased to last the life of HEV.

Run date: 3/30/2000

**Argonne National Laboratory: Center for Transportation Research**
**A Methodology for Projecting Parallel Hybrid Electric Vehicle Cost**
**(All costs are in 1995 dollars. Battery costs estimated for the HEVTECA project.)**
**HEVTECA (Parallel, Mild Grid-independent, UL Steel, HP Batt, 8-12s Z60 Time, APU=6.5% Grade+0.5*Gap): ADVISOR-2 Components Matching**

| | Vehicle type: **Midsize Car (MHV)** Z60 Time: **12 seconds (B)** Battery type: **NiMH (High Power)** | | | | Vehicle type: **Midsize Car (MHV)** Z60 Time: **10 seconds (B)** Battery type: **NiMH (High Power)** | | | | Vehicle type: **Midsize Car (MHV)** Z60 Time: **8 seconds (B)** Battery type: **NiMH (High Power)** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Item** | **2005** | **2010** | **2015** | **2020** | **2005** | **2010** | **2015** | **2020** | **2005** | **2010** | **2015** | **2020** |
| | **Purchase Price** | | | | **Purchase Price** | | | | **Purchase Price** | | | |
| **Conventional Vehicle** | $ 21,200 | $ 21,200 | $ 21,200 | $ 21,200 | $ 22,500 | $ 22,500 | $ 22,500 | $ 22,500 | $ 25,100 | $ 25,100 | $ 25,100 | $ 25,100 |
| **Hybrid Electric Vehicle** | | | | | | | | | | | | |
| Common components | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 |
| Additional aluminum cost | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - |
| Auxiliary Power Unit | $ 3,460 | $ 3,530 | $ 3,500 | $ 3,620 | $ 3,980 | $ 4,030 | $ 3,970 | $ 4,170 | $ 4,880 | $ 4,870 | $ 4,800 | $ 4,930 |
| Generator | $ 690 | $ 590 | $ 530 | $ 520 | $ 870 | $ 740 | $ 660 | $ 630 | $ 1,020 | $ 840 | $ 740 | $ 700 |
| Inverter & Power Electronics | $ 1,370 | $ 1,100 | $ 900 | $ 800 | $ 1,730 | $ 1,350 | $ 1,080 | $ 960 | $ 2,480 | $ 1,870 | $ 1,460 | $ 1,250 |
| Motor | $ 690 | $ 590 | $ 530 | $ 520 | $ 890 | $ 760 | $ 660 | $ 630 | $ 1,350 | $ 1,110 | $ 920 | $ 870 |
| Transmission | $ 900 | $ 860 | $ 800 | $ 790 | $ 1,100 | $ 1,040 | $ 960 | $ 960 | $ 1,470 | $ 1,380 | $ 1,270 | $ 1,240 |
| System control | $ 420 | $ 410 | $ 390 | $ 350 | $ 420 | $ 410 | $ 390 | $ 350 | $ 420 | $ 410 | $ 390 | $ 350 |
| Other body parts | $ 400 | $ 390 | $ 380 | $ 370 | $ 400 | $ 390 | $ 380 | $ 370 | $ 400 | $ 390 | $ 380 | $ 370 |
| Additional HVAC Cost | $ 120 | $ 110 | $ 110 | $ 110 | $ 120 | $ 110 | $ 110 | $ 110 | $ 120 | $ 110 | $ 110 | $ 110 |
| First Battery Price | $ 1,270 | $ 1,050 | $ 860 | $ 800 | $ 2,020 | $ 1,640 | $ 1,350 | $ 1,260 | $ 3,590 | $ 2,820 | $ 2,390 | $ 2,110 |
| Total HEV Price | $ 25,590 | $ 24,900 | $ 24,270 | $ 24,150 | $ 27,800 | $ 26,740 | $ 25,830 | $ 25,710 | $ 32,000 | $ 30,070 | $ 28,730 | $ 28,200 |
| | **Operating Cost** | | | | **Operating Cost** | | | | **Operating Cost** | | | |
| **Conventional Vehicle** | | | | | | | | | | | | |
| Fuel cost (c/mi) | 4.26 | 4.28 | 4.28 | 4.21 | 4.87 | 4.93 | 4.95 | 4.91 | 6.02 | 5.97 | 5.89 | 5.72 |
| Non-fuel cost (c/mi) | 4.90 | 4.97 | 5.05 | 5.20 | 4.90 | 4.97 | 5.05 | 5.20 | 4.90 | 4.97 | 5.05 | 5.20 |
| Total cost (c/mi) | 9.16 | 9.26 | 9.33 | 9.41 | 9.77 | 9.90 | 10.00 | 10.11 | 10.92 | 10.94 | 10.94 | 10.92 |
| **Hybrid Electric Vehicle** | | | | | | | | | | | | |
| Electricity cost (c/mi) | - | - | - | - | - | - | - | - | - | - | - | - |
| Fuel cost (c/mi) | 3.32 | 3.24 | 3.15 | 3.05 | 3.42 | 3.36 | 3.28 | 3.19 | 3.74 | 3.63 | 3.51 | 3.38 |
| Non-fuel cost (c/mi) | 5.55 | 5.63 | 5.72 | 5.89 | 5.55 | 5.63 | 5.72 | 5.89 | 5.55 | 5.63 | 5.72 | 5.89 |
| Battery cost (c/mi) | 1.54 | 1.21 | 0.95 | 0.90 | 2.45 | 1.88 | 1.50 | 1.41 | 4.35 | 3.24 | 2.65 | 2.37 |
| Total cost (c/mi) | 10.41 | 10.08 | 9.82 | 9.84 | 11.42 | 10.88 | 10.49 | 10.49 | 13.64 | 12.51 | 11.88 | 11.64 |
| | **Life-cycle Cost** | | | | **Life-cycle Cost** | | | | **Life-cycle Cost** | | | |
| **Conventional Vehicle** | | | | | | | | | | | | |
| Purchase Price (c/mi) | 20.80 | 20.50 | 20.20 | 20.20 | 22.08 | 21.75 | 21.44 | 21.44 | 24.63 | 24.27 | 23.91 | 23.91 |
| Operating Cost (c/mi) | 9.16 | 9.26 | 9.33 | 9.41 | 9.77 | 9.90 | 10.00 | 10.11 | 10.92 | 10.94 | 10.94 | 10.92 |
| Less Scrappage Value (c/mi) | (0.13) | (0.13) | (0.12) | (0.12) | (0.14) | (0.14) | (0.13) | (0.13) | (0.15) | (0.15) | (0.15) | (0.15) |
| Total Life-cycle Cost (c/mi) | 29.84 | 29.62 | 29.40 | 29.48 | 31.71 | 31.52 | 31.31 | 31.41 | 35.39 | 35.06 | 34.71 | 34.69 |
| **Hybrid Electric Vehicle** | | | | | | | | | | | | |
| Purchase Price - Battery (c/mi) | 23.86 | 23.06 | 22.30 | 22.25 | 25.30 | 24.27 | 23.32 | 23.30 | 27.88 | 26.34 | 25.10 | 24.86 |
| Operating Cost (c/mi) | 10.41 | 10.08 | 9.82 | 9.84 | 11.42 | 10.88 | 10.49 | 10.49 | 13.64 | 12.51 | 11.88 | 11.64 |
| Less Scrappage Value (c/mi) | (0.15) | (0.14) | (0.14) | (0.14) | (0.16) | (0.15) | (0.14) | (0.14) | (0.18) | (0.16) | (0.15) | (0.15) |
| Total Life-cycle Cost (c/mi) | 34.12 | 33.00 | 31.99 | 31.95 | 36.56 | 34.99 | 33.67 | 33.64 | 41.34 | 38.69 | 36.82 | 36.34 |
| | **Important HEV Parameters** | | | | **Important HEV Parameters** | | | | **Important HEV Parameters** | | | |
| Motor power (kW): Peak | 15 | 14 | 13 | 13 | 23 | 22 | 20 | 20 | 41 | 39 | 35 | 34 |
| Motor power (kW): Constant | 11 | 10 | 9 | 9 | 16 | 15 | 14 | 14 | 28 | 27 | 24 | 24 |
| APU power (kW) | 57 | 55 | 51 | 50 | 68 | 65 | 60 | 60 | 87 | 82 | 76 | 74 |
| Generator power (kW) | 15 | 14 | 13 | 13 | 22 | 21 | 20 | 20 | 28 | 26 | 25 | 24 |
| Battery power (kW) | 17 | 16 | 14 | 14 | 27 | 25 | 22 | 22 | 48 | 43 | 39 | 37 |
| Battery energy (kWh) | 1.5 | 1.4 | 1.2 | 1.2 | 2.3 | 2.2 | 1.9 | 1.9 | 4.2 | 3.8 | 3.4 | 3.2 |
| Battery mass (kg) | 34 | 31 | 26 | 24 | 54 | 48 | 40 | 38 | 96 | 83 | 71 | 65 |
| Total vehicle mass (kg) | 1,270 | 1,246 | 1,214 | 1,202 | 1,351 | 1,321 | 1,280 | 1,269 | 1,504 | 1,453 | 1,400 | 1,373 |
| Zero-to-60 mph time(s) | 12.0 | 12.0 | 12.0 | 12.0 | 10.0 | 10.0 | 10.0 | 10.0 | 8.0 | 8.0 | 8.0 | 8.0 |
| Estimated all-elec range (mi) | 4 | 4 | 4 | 4 | 6 | 6 | 5 | 6 | 11 | 10 | 10 | 10 |

Parallel Grid-independent MHV: HEVCOST Model Run with ADVISOR mpg (for CV & HEV) dated 11/28/99. The default battery life used, requires one battery replaceme
Run dated: 3/30/2000 (The MHVs' APU are sized in-between the corresponding CV and FHV capable of 6.5% grade.)

**Argonne National Laboratory: Center for Transportation Research**

**A Methodology for Projecting Parallel Hybrid Electric Vehicle Cost**

**(All costs are in 1995 dollars. Battery costs estimated for the HEVTECA project.)**

**HEVTECA (Parallel, Mild Grid-independent, UL Steel, HP Batt thru HEV Life, 8-12s Z60 Time, APU=6.5% Grade+0.5*Gap): ADVISOR-2 Components Matching**

| | Vehicle type: **Midsize Car (MHV)**<br>Z60 Time: **12 seconds (B)**<br>Battery type: **NiMH (High Power)** | | | | Vehicle type: **Midsize Car (MHV)**<br>Z60 Time: **10 seconds (B)**<br>Battery type: **NiMH (High Power)** | | | | Vehicle type: **Midsize Car (MHV)**<br>Z60 Time: **8 seconds (B)**<br>Battery type: **NiMH (High Power)** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Item** | **2005** | **2010** | **2015** | **2020** | **2005** | **2010** | **2015** | **2020** | **2005** | **2010** | **2015** | **2020** |
| | **Purchase Price** | | | | **Purchase Price** | | | | **Purchase Price** | | | |
| **Conventional Vehicle** | $ 21,200 | $ 21,200 | $ 21,200 | $ 21,200 | $ 22,500 | $ 22,500 | $ 22,500 | $ 22,500 | $ 25,100 | $ 25,100 | $ 25,100 | $ 25,100 |
| **Hybrid Electric Vehicle** | | | | | | | | | | | | |
| Common components | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 |
| Additional aluminum cost | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - |
| Auxiliary Power Unit | $ 3,460 | $ 3,530 | $ 3,500 | $ 3,620 | $ 3,980 | $ 4,030 | $ 3,970 | $ 4,170 | $ 4,880 | $ 4,870 | $ 4,800 | $ 4,930 |
| Generator | $ 690 | $ 590 | $ 530 | $ 520 | $ 870 | $ 740 | $ 660 | $ 630 | $ 1,020 | $ 840 | $ 740 | $ 700 |
| Inverter & Power Electronics | $ 1,370 | $ 1,100 | $ 900 | $ 800 | $ 1,730 | $ 1,350 | $ 1,080 | $ 960 | $ 2,480 | $ 1,870 | $ 1,460 | $ 1,250 |
| Motor | $ 690 | $ 590 | $ 530 | $ 520 | $ 890 | $ 760 | $ 660 | $ 630 | $ 1,350 | $ 1,110 | $ 920 | $ 870 |
| Transmission | $ 900 | $ 860 | $ 800 | $ 790 | $ 1,100 | $ 1,040 | $ 960 | $ 960 | $ 1,470 | $ 1,380 | $ 1,270 | $ 1,240 |
| System control | $ 420 | $ 410 | $ 390 | $ 350 | $ 420 | $ 410 | $ 390 | $ 350 | $ 420 | $ 410 | $ 390 | $ 350 |
| Other body parts | $ 400 | $ 390 | $ 380 | $ 370 | $ 400 | $ 390 | $ 380 | $ 370 | $ 400 | $ 390 | $ 380 | $ 370 |
| Additional HVAC Cost | $ 120 | $ 110 | $ 110 | $ 110 | $ 120 | $ 110 | $ 110 | $ 110 | $ 120 | $ 110 | $ 110 | $ 110 |
| First Battery Price | $ 1,270 | $ 1,050 | $ 860 | $ 800 | $ 2,020 | $ 1,640 | $ 1,350 | $ 1,260 | $ 3,590 | $ 2,820 | $ 2,390 | $ 2,110 |
| Total HEV Price | $ 25,590 | $ 24,900 | $ 24,270 | $ 24,150 | $ 27,800 | $ 26,740 | $ 25,830 | $ 25,710 | $ 32,000 | $ 30,070 | $ 28,730 | $ 28,200 |
| | **Operating Cost** | | | | **Operating Cost** | | | | **Operating Cost** | | | |
| **Conventional Vehicle** | | | | | | | | | | | | |
| Fuel cost (c/mi) | 4.26 | 4.28 | 4.28 | 4.21 | 4.87 | 4.93 | 4.95 | 4.91 | 6.02 | 5.97 | 5.89 | 5.72 |
| Non-fuel cost (c/mi) | 4.90 | 4.97 | 5.05 | 5.20 | 4.90 | 4.97 | 5.05 | 5.20 | 4.90 | 4.97 | 5.05 | 5.20 |
| Total cost (c/mi) | 9.16 | 9.26 | 9.33 | 9.41 | 9.77 | 9.90 | 10.00 | 10.11 | 10.92 | 10.94 | 10.94 | 10.92 |
| **Hybrid Electric Vehicle** | | | | | | | | | | | | |
| Electricity cost (c/mi) | - | - | - | - | - | - | - | - | - | - | - | - |
| Fuel cost (c/mi) | 3.32 | 3.24 | 3.15 | 3.05 | 3.42 | 3.36 | 3.28 | 3.19 | 3.74 | 3.63 | 3.51 | 3.38 |
| Non-fuel cost (c/mi) | 5.55 | 5.63 | 5.72 | 5.89 | 5.55 | 5.63 | 5.72 | 5.89 | 5.55 | 5.63 | 5.72 | 5.89 |
| Battery cost (c/mi) | 1.25 | 1.02 | 0.82 | 0.76 | 1.98 | 1.59 | 1.29 | 1.20 | 3.52 | 2.73 | 2.28 | 2.01 |
| Total cost (c/mi) | 10.12 | 9.89 | 9.69 | 9.70 | 10.96 | 10.58 | 10.28 | 10.28 | 12.81 | 11.99 | 11.50 | 11.28 |
| | **Life-cycle Cost** | | | | **Life-cycle Cost** | | | | **Life-cycle Cost** | | | |
| **Conventional Vehicle** | | | | | | | | | | | | |
| Purchase Price (c/mi) | 20.80 | 20.50 | 20.20 | 20.20 | 22.08 | 21.75 | 21.44 | 21.44 | 24.63 | 24.27 | 23.91 | 23.91 |
| Operating Cost (c/mi) | 9.16 | 9.26 | 9.33 | 9.41 | 9.77 | 9.90 | 10.00 | 10.11 | 10.92 | 10.94 | 10.94 | 10.92 |
| Less Scrappage Value (c/mi) | (0.13) | (0.13) | (0.12) | (0.12) | (0.14) | (0.14) | (0.13) | (0.13) | (0.15) | (0.15) | (0.15) | (0.15) |
| Total Life-cycle Cost (c/mi) | 29.84 | 29.62 | 29.40 | 29.48 | 31.71 | 31.52 | 31.31 | 31.41 | 35.39 | 35.06 | 34.71 | 34.69 |
| **Hybrid Electric Vehicle** | | | | | | | | | | | | |
| Purchase Price - Battery (c/mi) | 23.86 | 23.06 | 22.30 | 22.25 | 25.30 | 24.27 | 23.32 | 23.30 | 27.88 | 26.34 | 25.10 | 24.86 |
| Operating Cost (c/mi) | 10.12 | 9.89 | 9.69 | 9.70 | 10.96 | 10.58 | 10.28 | 10.28 | 12.81 | 11.99 | 11.50 | 11.28 |
| Less Scrappage Value (c/mi) | (0.15) | (0.14) | (0.14) | (0.14) | (0.16) | (0.15) | (0.14) | (0.14) | (0.18) | (0.16) | (0.15) | (0.15) |
| Total Life-cycle Cost (c/mi) | 33.83 | 32.81 | 31.85 | 31.81 | 36.09 | 34.69 | 33.46 | 33.43 | 40.52 | 38.17 | 36.45 | 35.99 |
| | **Important HEV Parameters** | | | | **Important HEV Parameters** | | | | **Important HEV Parameters** | | | |
| Motor power (kW): Peak | 15 | 14 | 13 | 13 | 23 | 22 | 20 | 20 | 41 | 39 | 35 | 34 |
| Motor power (kW): Constant | 11 | 10 | 9 | 9 | 16 | 15 | 14 | 14 | 28 | 27 | 24 | 24 |
| APU power (kW) | 57 | 55 | 51 | 50 | 68 | 65 | 60 | 60 | 87 | 82 | 76 | 74 |
| Generator power (kW) | 15 | 14 | 13 | 13 | 22 | 21 | 20 | 20 | 28 | 26 | 25 | 24 |
| Battery power (kW) | 17 | 16 | 14 | 14 | 27 | 25 | 22 | 22 | 48 | 43 | 39 | 37 |
| Battery energy (kWh) | 1.5 | 1.4 | 1.2 | 1.2 | 2.3 | 2.2 | 1.9 | 1.9 | 4.2 | 3.8 | 3.4 | 3.2 |
| Battery mass (kg) | 34 | 31 | 26 | 24 | 54 | 48 | 40 | 38 | 96 | 83 | 71 | 65 |
| Total vehicle mass (kg) | 1,270 | 1,246 | 1,214 | 1,202 | 1,351 | 1,321 | 1,280 | 1,269 | 1,504 | 1,453 | 1,400 | 1,373 |
| Zero-to-60 mph time(s) | 12.0 | 12.0 | 12.0 | 12.0 | 10.0 | 10.0 | 10.0 | 10.0 | 8.0 | 8.0 | 8.0 | 8.0 |
| Estimated all-elec range (mi) | 4 | 4 | 4 | 4 | 6 | 6 | 5 | 6 | 11 | 10 | 10 | 10 |

Parallel Grid-independent MHV: HEVCOST Model Run with ADVISOR mpg (for CV & HEV) dated 11/28/99. The battery life increased to last the life of HEV.

Run dated: 3/30/2000 (The MHVs' APU are sized in-between the corresponding CV and FHV capable of 6.5% grade.)

**Argonne National Laboratory: Center for Transportation Research**

**A Methodology for Projecting Parallel Hybrid Electric Vehicle Cost**

**(All costs are in 1995 dollars. Battery costs estimated for the HEVTECA project.)**

**HEVTECA (Parallel, Mild Grid-independent, UL Steel, HP Batt thru HEV Life, 8-12s Z60 Time, APU=6.5% Grade+0.5*Gap): ADVISOR-2 Components Matching**

| | Vehicle type: **Midsize Car (MHV)** Z60 Time: **12 seconds (B)** Battery type: **NiMH (High Power)** | | | | Vehicle type: **Midsize Car (MHV)** Z60 Time: **10 seconds (B)** Battery type: **NiMH (High Power)** | | | | Vehicle type: **Midsize Car (MHV)** Z60 Time: **8 seconds (B)** Battery type: **NiMH (High Power)** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Item** | **2005** | **2010** | **2015** | **2020** | **2005** | **2010** | **2015** | **2020** | **2005** | **2010** | **2015** | **2020** |
| | **Purchase Price** | | | | **Purchase Price** | | | | **Purchase Price** | | | |
| **Conventional Vehicle** | $ 21,200 | $ 21,200 | $ 21,200 | $ 21,200 | $ 22,500 | $ 22,500 | $ 22,500 | $ 22,500 | $ 25,100 | $ 25,100 | $ 25,100 | $ 25,100 |
| **Hybrid Electric Vehicle** | | | | | | | | | | | | |
| Common components | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 |
| Additional aluminum cost | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - |
| Auxiliary Power Unit | $ 3,460 | $ 3,530 | $ 3,500 | $ 3,620 | $ 3,980 | $ 4,030 | $ 3,970 | $ 4,170 | $ 4,880 | $ 4,870 | $ 4,800 | $ 4,930 |
| Generator | $ 690 | $ 590 | $ 530 | $ 520 | $ 870 | $ 740 | $ 660 | $ 630 | $ 1,020 | $ 840 | $ 740 | $ 700 |
| Inverter & Power Electronics | $ 1,370 | $ 1,100 | $ 900 | $ 800 | $ 1,730 | $ 1,350 | $ 1,080 | $ 960 | $ 2,480 | $ 1,870 | $ 1,460 | $ 1,250 |
| Motor | $ 690 | $ 590 | $ 530 | $ 520 | $ 890 | $ 760 | $ 660 | $ 630 | $ 1,350 | $ 1,110 | $ 920 | $ 870 |
| Transmission | $ 900 | $ 860 | $ 800 | $ 790 | $ 1,100 | $ 1,040 | $ 960 | $ 960 | $ 1,470 | $ 1,380 | $ 1,270 | $ 1,240 |
| System control | $ 420 | $ 410 | $ 390 | $ 350 | $ 420 | $ 410 | $ 390 | $ 350 | $ 420 | $ 410 | $ 390 | $ 350 |
| Other body parts | $ 400 | $ 390 | $ 380 | $ 370 | $ 400 | $ 390 | $ 380 | $ 370 | $ 400 | $ 390 | $ 380 | $ 370 |
| Additional HVAC Cost | $ 120 | $ 110 | $ 110 | $ 110 | $ 120 | $ 110 | $ 110 | $ 110 | $ 120 | $ 110 | $ 110 | $ 110 |
| First Battery Price | $ 1,270 | $ 1,050 | $ 860 | $ 800 | $ 2,020 | $ 1,640 | $ 1,350 | $ 1,260 | $ 3,590 | $ 2,820 | $ 2,390 | $ 2,110 |
| Total HEV Price | $ 25,590 | $ 24,900 | $ 24,270 | $ 24,150 | $ 27,800 | $ 26,740 | $ 25,830 | $ 25,710 | $ 32,000 | $ 30,070 | $ 28,730 | $ 28,200 |
| | **Operating Cost** | | | | **Operating Cost** | | | | **Operating Cost** | | | |
| **Conventional Vehicle** | | | | | | | | | | | | |
| Fuel cost (c/mi) | 4.26 | 4.28 | 4.28 | 4.21 | 4.87 | 4.93 | 4.95 | 4.91 | 6.02 | 5.97 | 5.89 | 5.72 |
| Non-fuel cost (c/mi) | 4.90 | 4.97 | 5.05 | 5.20 | 4.90 | 4.97 | 5.05 | 5.20 | 4.90 | 4.97 | 5.05 | 5.20 |
| Total cost (c/mi) | 9.16 | 9.26 | 9.33 | 9.41 | 9.77 | 9.90 | 10.00 | 10.11 | 10.92 | 10.94 | 10.94 | 10.92 |
| **Hybrid Electric Vehicle** | | | | | | | | | | | | |
| Electricity cost (c/mi) | - | - | - | - | - | - | - | - | - | - | - | - |
| Fuel cost (c/mi) | 3.32 | 3.24 | 3.15 | 3.05 | 3.42 | 3.36 | 3.28 | 3.19 | 3.74 | 3.63 | 3.51 | 3.38 |
| Non-fuel cost (c/mi) | 5.55 | 5.63 | 5.72 | 5.89 | 5.55 | 5.63 | 5.72 | 5.89 | 5.55 | 5.63 | 5.72 | 5.89 |
| Battery cost (c/mi) | 1.25 | 1.02 | 0.82 | 0.76 | 1.98 | 1.59 | 1.29 | 1.20 | 3.52 | 2.73 | 2.28 | 2.01 |
| Total cost (c/mi) | 10.12 | 9.89 | 9.69 | 9.70 | 10.96 | 10.58 | 10.28 | 10.28 | 12.81 | 11.99 | 11.50 | 11.28 |
| | **Life-cycle Cost** | | | | **Life-cycle Cost** | | | | **Life-cycle Cost** | | | |
| **Conventional Vehicle** | | | | | | | | | | | | |
| Purchase Price (c/mi) | 20.80 | 20.50 | 20.20 | 20.20 | 22.08 | 21.75 | 21.44 | 21.44 | 24.63 | 24.27 | 23.91 | 23.91 |
| Operating Cost (c/mi) | 9.16 | 9.26 | 9.33 | 9.41 | 9.77 | 9.90 | 10.00 | 10.11 | 10.92 | 10.94 | 10.94 | 10.92 |
| Less Scrappage Value (c/mi) | (0.13) | (0.13) | (0.12) | (0.12) | (0.14) | (0.14) | (0.13) | (0.13) | (0.15) | (0.15) | (0.15) | (0.15) |
| Total Life-cycle Cost (c/mi) | 29.84 | 29.62 | 29.40 | 29.48 | 31.71 | 31.52 | 31.31 | 31.41 | 35.39 | 35.06 | 34.71 | 34.69 |
| **Hybrid Electric Vehicle** | | | | | | | | | | | | |
| Purchase Price - Battery (c/mi) | 23.86 | 23.06 | 22.30 | 22.25 | 25.30 | 24.27 | 23.32 | 23.30 | 27.88 | 26.34 | 25.10 | 24.86 |
| Operating Cost (c/mi) | 10.12 | 9.89 | 9.69 | 9.70 | 10.96 | 10.58 | 10.28 | 10.28 | 12.81 | 11.99 | 11.50 | 11.28 |
| Less Scrappage Value (c/mi) | (0.15) | (0.14) | (0.14) | (0.14) | (0.16) | (0.15) | (0.14) | (0.14) | (0.18) | (0.16) | (0.15) | (0.15) |
| Total Life-cycle Cost (c/mi) | 33.83 | 32.81 | 31.85 | 31.81 | 36.09 | 34.69 | 33.46 | 33.43 | 40.52 | 38.17 | 36.45 | 35.99 |
| | **Important HEV Parameters** | | | | **Important HEV Parameters** | | | | **Important HEV Parameters** | | | |
| Motor power (kW): Peak | 15 | 14 | 13 | 13 | 23 | 22 | 20 | 20 | 41 | 39 | 35 | 34 |
| Motor power (kW): Constant | 11 | 10 | 9 | 9 | 16 | 15 | 14 | 14 | 28 | 27 | 24 | 24 |
| APU power (kW) | 57 | 55 | 51 | 50 | 68 | 65 | 60 | 60 | 87 | 82 | 76 | 74 |
| Generator power (kW) | 15 | 14 | 13 | 13 | 22 | 21 | 20 | 20 | 28 | 26 | 25 | 24 |
| Battery power (kW) | 17 | 16 | 14 | 14 | 27 | 25 | 22 | 22 | 48 | 43 | 39 | 37 |
| Battery energy (kWh) | 1.5 | 1.4 | 1.2 | 1.2 | 2.3 | 2.2 | 1.9 | 1.9 | 4.2 | 3.8 | 3.4 | 3.2 |
| Battery mass (kg) | 34 | 31 | 26 | 24 | 54 | 48 | 40 | 38 | 96 | 83 | 71 | 65 |
| Total vehicle mass (kg) | 1,270 | 1,246 | 1,214 | 1,202 | 1,351 | 1,321 | 1,280 | 1,269 | 1,504 | 1,453 | 1,400 | 1,373 |
| Zero-to-60 mph time(s) | 12.0 | 12.0 | 12.0 | 12.0 | 10.0 | 10.0 | 10.0 | 10.0 | 8.0 | 8.0 | 8.0 | 8.0 |
| Estimated all-elec range (mi) | 4 | 4 | 4 | 4 | 6 | 6 | 5 | 6 | 11 | 10 | 10 | 10 |

Parallel Grid-independent MHV: HEVCOST Model Run with ADVISOR mpg (for CV & HEV) dated 11/28/99. The battery life increased to last the life of HEV.

Run dated: 3/30/2000 (The MHVs' APU are sized in-between the corresponding CV and FHV capable of 6.5% grade.)

**Argonne National Laboratory: Center for Transportation Research**

**A Methodology for Projecting Series Hybrid Electric Vehicle Cost**

**(All costs are in 1995 dollars. Battery costs Estimated for the HEVTECA Project.)**

**HEV (Series, Grid-Independent, UL Steel, HP Batt, 8-12s Z60 Time) ADVISOR2 Components Matching**

| | Vehicle type: **Midsize Car**<br>Z60 Time: **12 seconds**<br>Battery type: **NiMH (High Power)** | | | | Vehicle type: **Midsize Car**<br>Z60 Time: **10 seconds**<br>Battery type: **NiMH (High Power)** | | | | Vehicle type: **Midsize Car**<br>Z60 Time: **8 seconds**<br>Battery type: **NiMH (High Power)** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Item** | **2005** | **2010** | **2015** | **2020** | **2005** | **2010** | **2015** | **2020** | **2005** | **2010** | **2015** | **2020** |
| | **Purchase Price** | | | | **Purchase Price** | | | | **Purchase Price** | | | |
| **Conventional Vehicle** | $ 21,200 | $ 21,200 | $ 21,200 | $ 21,200 | $ 22,500 | $ 22,500 | $ 22,500 | $ 22,500 | $ 25,100 | $ 25,100 | $ 25,100 | $ 25,100 |
| **Hybrid Electric Vehicle** | | | | | | | | | | | | |
| Common components | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 |
| Additional aluminum cost | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - |
| Auxiliary Power Unit | $ 3,410 | $ 3,380 | $ 3,390 | $ 3,400 | $ 3,500 | $ 3,430 | $ 3,440 | $ 3,510 | $ 3,690 | $ 3,580 | $ 3,600 | $ 3,620 |
| Generator | $ 1,680 | $ 1,330 | $ 1,150 | $ 1,050 | $ 1,730 | $ 1,350 | $ 1,150 | $ 1,080 | $ 1,810 | $ 1,410 | $ 1,200 | $ 1,110 |
| Inverter & Power Electronics | $ 3,890 | $ 2,920 | $ 2,290 | $ 1,930 | $ 4,610 | $ 3,410 | $ 2,630 | $ 2,270 | $ 5,900 | $ 4,320 | $ 3,300 | $ 2,790 |
| Motor | $ 2,240 | $ 1,760 | $ 1,520 | $ 1,410 | $ 2,680 | $ 2,090 | $ 1,780 | $ 1,640 | $ 3,490 | $ 2,670 | $ 2,240 | $ 2,070 |
| Gear Drive | $ 280 | $ 250 | $ 240 | $ 230 | $ 340 | $ 300 | $ 290 | $ 280 | $ 450 | $ 400 | $ 380 | $ 370 |
| System control | $ 420 | $ 410 | $ 390 | $ 350 | $ 420 | $ 410 | $ 390 | $ 350 | $ 420 | $ 410 | $ 390 | $ 350 |
| Other body parts | $ 400 | $ 390 | $ 380 | $ 370 | $ 400 | $ 390 | $ 380 | $ 370 | $ 400 | $ 390 | $ 380 | $ 370 |
| Additional HVAC Cost | $ 120 | $ 110 | $ 110 | $ 110 | $ 120 | $ 110 | $ 110 | $ 110 | $ 120 | $ 110 | $ 110 | $ 110 |
| First Battery Price | $ 2,470 | $ 1,970 | $ 1,720 | $ 1,540 | $ 3,810 | $ 3,010 | $ 2,630 | $ 2,400 | $ 6,280 | $ 4,910 | $ 4,280 | $ 3,830 |
| Total HEV Price | $ 31,200 | $ 28,800 | $ 27,500 | $ 26,700 | $ 33,900 | $ 30,800 | $ 29,100 | $ 28,300 | $ 38,900 | $ 34,500 | $ 32,200 | $ 30,900 |
| | **Operating Cost** | | | | **Operating Cost** | | | | **Operating Cost** | | | |
| **Conventional Vehicle** | | | | | | | | | | | | |
| Fuel cost (c/mi) | 4.26 | 4.28 | 4.28 | 4.21 | 4.87 | 4.93 | 4.95 | 4.91 | 6.02 | 5.97 | 5.89 | 5.72 |
| Non-fuel cost (c/mi) | 4.90 | 4.97 | 5.05 | 5.20 | 4.90 | 4.97 | 5.05 | 5.20 | 4.90 | 4.97 | 5.05 | 5.20 |
| Total cost (c/mi) | 9.16 | 9.26 | 9.33 | 9.41 | 9.77 | 9.90 | 10.00 | 10.11 | 10.92 | 10.94 | 10.94 | 10.92 |
| **Hybrid Electric Vehicle** | | | | | | | | | | | | |
| Electricity cost (c/mi) | - | - | - | - | - | - | - | - | - | - | - | - |
| Fuel cost (c/mi) | 3.53 | 3.44 | 3.34 | 3.24 | 3.63 | 3.52 | 3.40 | 3.31 | 3.75 | 3.64 | 3.52 | 3.39 |
| Non-fuel cost (c/mi) | 5.55 | 5.63 | 5.72 | 5.89 | 5.55 | 5.63 | 5.72 | 5.89 | 5.55 | 5.63 | 5.72 | 5.89 |
| Battery cost (c/mi) | 2.99 | 2.26 | 1.90 | 1.73 | 4.62 | 3.46 | 2.92 | 2.69 | 7.61 | 5.65 | 4.75 | 4.29 |
| Total cost (c/mi) | 12.07 | 11.34 | 10.97 | 10.85 | 13.79 | 12.62 | 12.04 | 11.89 | 16.90 | 14.92 | 13.98 | 13.57 |
| | **Life-cycle Cost** | | | | **Life-cycle Cost** | | | | **Life-cycle Cost** | | | |
| **Conventional Vehicle** | | | | | | | | | | | | |
| Purchase Price (c/mi) | 20.80 | 20.50 | 20.20 | 20.20 | 22.08 | 21.75 | 21.44 | 21.44 | 24.63 | 24.27 | 23.91 | 23.91 |
| Operating Cost (c/mi) | 9.16 | 9.26 | 9.33 | 9.41 | 9.77 | 9.90 | 10.00 | 10.11 | 10.92 | 10.94 | 10.94 | 10.92 |
| Less Scrappage Value (c/mi) | (0.13) | (0.13) | (0.12) | (0.12) | (0.14) | (0.14) | (0.13) | (0.13) | (0.15) | (0.15) | (0.15) | (0.15) |
| Total Life-cycle Cost (c/mi) | 29.84 | 29.62 | 29.40 | 29.48 | 31.71 | 31.52 | 31.31 | 31.41 | 35.39 | 35.06 | 34.71 | 34.69 |
| **Hybrid Electric Vehicle** | | | | | | | | | | | | |
| Purchase Price - Battery (c/mi) | 28.19 | 25.94 | 24.56 | 23.97 | 29.53 | 26.87 | 25.22 | 24.68 | 32.01 | 28.61 | 26.60 | 25.79 |
| Operating Cost (c/mi) | 12.07 | 11.34 | 10.97 | 10.85 | 13.79 | 12.62 | 12.04 | 11.89 | 16.90 | 14.92 | 13.98 | 13.57 |
| Less Scrappage Value (c/mi) | (0.18) | (0.16) | (0.15) | (0.15) | (0.19) | (0.17) | (0.16) | (0.15) | (0.20) | (0.18) | (0.16) | (0.16) |
| Total Life-cycle Cost (c/mi) | 40.08 | 37.11 | 35.38 | 34.68 | 43.13 | 39.32 | 37.10 | 36.42 | 48.71 | 43.35 | 40.42 | 39.20 |
| | **Important HEV Parameters** | | | | **Important HEV Parameters** | | | | **Important HEV Parameters** | | | |
| Motor power (kW): Peak | 76 | 71 | 69 | 67 | 93 | 87 | 84 | 81 | 125 | 115 | 110 | 107 |
| Motor power (kW): Constant | 52 | 49 | 47 | 46 | 64 | 60 | 58 | 56 | 85 | 79 | 75 | 73 |
| APU power (kW) | 56 | 52 | 49 | 46 | 58 | 53 | 50 | 48 | 62 | 56 | 53 | 50 |
| Generator power (kW) | 54 | 50 | 48 | 45 | 56 | 51 | 48 | 47 | 59 | 54 | 51 | 49 |
| Battery power (kW) | 33 | 30 | 28 | 27 | 51 | 46 | 43 | 42 | 84 | 75 | 70 | 67 |
| Battery energy (kWh) | 2.9 | 2.7 | 2.5 | 2.3 | 4.4 | 4.1 | 3.8 | 3.6 | 7.3 | 6.7 | 6.1 | 5.8 |
| Battery mass (kg) | 66 | 58 | 51 | 47 | 102 | 89 | 79 | 73 | 168 | 144 | 128 | 117 |
| Total vehicle mass (kg) | 1,386 | 1,341 | 1,310 | 1,281 | 1,457 | 1,401 | 1,364 | 1,336 | 1,591 | 1,513 | 1,465 | 1,426 |
| Acceleration time 0-60 mph (s) | 12.0 | 12.0 | 12.0 | 12.0 | 10.0 | 10.0 | 10.0 | 10.0 | 8.0 | 8.0 | 8.0 | 8.0 |
| Estimated all-elec range (mi) | 5 | 5 | 5 | 5 | 8 | 8 | 8 | 8 | 14 | 13 | 12 | 13 |

Series Grid-independent FHV: HEVCOST Model Run with ADVISOR mpg (for CV & HEV) dated 12/1/99. The default battery life used, requires one battery replacement.

Run date: 3/30/2000

**Argonne National Laboratory: Center for Transportation Research**

**A Methodology for Projecting Series Hybrid Electric Vehicle Cost**

**(All costs are in 1995 dollars. Battery costs Estimated for the HEVTECA Project.)**

**HEV (Series, Grid-Independent, UL Steel, HP Batt thru HEV Life, 8-12s Z60 Time) ADVISOR2 Components Matching**

| | Vehicle type: **Midsize Car**<br>Z60 Time: **12 seconds**<br>Battery type: **NiMH (High Power)** | | | | Vehicle type: **Midsize Car**<br>Z60 Time: **10 seconds**<br>Battery type: **NiMH (High Power)** | | | | Vehicle type: **Midsize Car**<br>Z60 Time: **8 seconds**<br>Battery type: **NiMH (High Power)** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Item** | **2005** | **2010** | **2015** | **2020** | **2005** | **2010** | **2015** | **2020** | **2005** | **2010** | **2015** | **2020** |
| | **Purchase Price** | | | | **Purchase Price** | | | | **Purchase Price** | | | |
| **Conventional Vehicle** | $ 21,200 | $ 21,200 | $ 21,200 | $ 21,200 | $ 22,500 | $ 22,500 | $ 22,500 | $ 22,500 | $ 25,100 | $ 25,100 | $ 25,100 | $ 25,100 |
| **Hybrid Electric Vehicle** | | | | | | | | | | | | |
| Common components | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 |
| Additional aluminum cost | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - |
| Auxiliary Power Unit | $ 3,410 | $ 3,380 | $ 3,390 | $ 3,400 | $ 3,500 | $ 3,430 | $ 3,440 | $ 3,510 | $ 3,690 | $ 3,580 | $ 3,600 | $ 3,620 |
| Generator | $ 1,680 | $ 1,330 | $ 1,150 | $ 1,050 | $ 1,730 | $ 1,350 | $ 1,150 | $ 1,080 | $ 1,810 | $ 1,410 | $ 1,200 | $ 1,110 |
| Inverter & Power Electronics | $ 3,890 | $ 2,920 | $ 2,290 | $ 1,930 | $ 4,610 | $ 3,410 | $ 2,630 | $ 2,270 | $ 5,900 | $ 4,320 | $ 3,300 | $ 2,790 |
| Motor | $ 2,240 | $ 1,760 | $ 1,520 | $ 1,410 | $ 2,680 | $ 2,090 | $ 1,780 | $ 1,640 | $ 3,490 | $ 2,670 | $ 2,240 | $ 2,070 |
| Gear Drive | $ 280 | $ 250 | $ 240 | $ 230 | $ 340 | $ 300 | $ 290 | $ 280 | $ 450 | $ 400 | $ 380 | $ 370 |
| System control | $ 420 | $ 410 | $ 390 | $ 350 | $ 420 | $ 410 | $ 390 | $ 350 | $ 420 | $ 410 | $ 390 | $ 350 |
| Other body parts | $ 400 | $ 390 | $ 380 | $ 370 | $ 400 | $ 390 | $ 380 | $ 370 | $ 400 | $ 390 | $ 380 | $ 370 |
| Additional HVAC Cost | $ 120 | $ 110 | $ 110 | $ 110 | $ 120 | $ 110 | $ 110 | $ 110 | $ 120 | $ 110 | $ 110 | $ 110 |
| First Battery Price | $ 2,470 | $ 1,970 | $ 1,720 | $ 1,540 | $ 3,810 | $ 3,010 | $ 2,630 | $ 2,400 | $ 6,280 | $ 4,910 | $ 4,280 | $ 3,830 |
| Total HEV Price | $ 31,200 | $ 28,800 | $ 27,500 | $ 26,700 | $ 33,900 | $ 30,800 | $ 29,100 | $ 28,300 | $ 38,900 | $ 34,500 | $ 32,200 | $ 30,900 |
| | **Operating Cost** | | | | **Operating Cost** | | | | **Operating Cost** | | | |
| **Conventional Vehicle** | | | | | | | | | | | | |
| Fuel cost (c/mi) | 4.26 | 4.28 | 4.28 | 4.21 | 4.87 | 4.93 | 4.95 | 4.91 | 6.02 | 5.97 | 5.89 | 5.72 |
| Non-fuel cost (c/mi) | 4.90 | 4.97 | 5.05 | 5.20 | 4.90 | 4.97 | 5.05 | 5.20 | 4.90 | 4.97 | 5.05 | 5.20 |
| Total cost (c/mi) | 9.16 | 9.26 | 9.33 | 9.41 | 9.77 | 9.90 | 10.00 | 10.11 | 10.92 | 10.94 | 10.94 | 10.92 |
| **Hybrid Electric Vehicle** | | | | | | | | | | | | |
| Electricity cost (c/mi) | - | - | - | - | - | - | - | - | - | - | - | - |
| Fuel cost (c/mi) | 3.53 | 3.44 | 3.34 | 3.24 | 3.63 | 3.52 | 3.40 | 3.31 | 3.75 | 3.64 | 3.52 | 3.39 |
| Non-fuel cost (c/mi) | 5.55 | 5.63 | 5.72 | 5.89 | 5.55 | 5.63 | 5.72 | 5.89 | 5.55 | 5.63 | 5.72 | 5.89 |
| Battery cost (c/mi) | 2.42 | 1.90 | 1.64 | 1.47 | 3.74 | 2.91 | 2.51 | 2.29 | 6.16 | 4.75 | 4.08 | 3.65 |
| Total cost (c/mi) | 11.50 | 10.98 | 10.70 | 10.59 | 12.91 | 12.07 | 11.63 | 11.49 | 15.46 | 14.02 | 13.31 | 12.93 |
| | **Life-cycle Cost** | | | | **Life-cycle Cost** | | | | **Life-cycle Cost** | | | |
| **Conventional Vehicle** | | | | | | | | | | | | |
| Purchase Price (c/mi) | 20.80 | 20.50 | 20.20 | 20.20 | 22.08 | 21.75 | 21.44 | 21.44 | 24.63 | 24.27 | 23.91 | 23.91 |
| Operating Cost (c/mi) | 9.16 | 9.26 | 9.33 | 9.41 | 9.77 | 9.90 | 10.00 | 10.11 | 10.92 | 10.94 | 10.94 | 10.92 |
| Less Scrappage Value (c/mi) | (0.13) | (0.13) | (0.12) | (0.12) | (0.14) | (0.14) | (0.13) | (0.13) | (0.15) | (0.15) | (0.15) | (0.15) |
| Total Life-cycle Cost (c/mi) | 29.84 | 29.62 | 29.40 | 29.48 | 31.71 | 31.52 | 31.31 | 31.41 | 35.39 | 35.06 | 34.71 | 34.69 |
| **Hybrid Electric Vehicle** | | | | | | | | | | | | |
| Purchase Price - Battery (c/mi) | 28.19 | 25.94 | 24.56 | 23.97 | 29.53 | 26.87 | 25.22 | 24.68 | 32.01 | 28.61 | 26.60 | 25.79 |
| Operating Cost (c/mi) | 11.50 | 10.98 | 10.70 | 10.59 | 12.91 | 12.07 | 11.63 | 11.49 | 15.46 | 14.02 | 13.31 | 12.93 |
| Less Scrappage Value (c/mi) | (0.18) | (0.16) | (0.15) | (0.15) | (0.19) | (0.17) | (0.16) | (0.15) | (0.20) | (0.18) | (0.16) | (0.16) |
| Total Life-cycle Cost (c/mi) | 39.51 | 36.76 | 35.11 | 34.42 | 42.26 | 38.76 | 36.69 | 36.01 | 47.27 | 42.45 | 39.75 | 38.56 |
| | **Important HEV Parameters** | | | | **Important HEV Parameters** | | | | **Important HEV Parameters** | | | |
| Motor power (kW): Peak | 76 | 71 | 69 | 67 | 93 | 87 | 84 | 81 | 125 | 115 | 110 | 107 |
| Motor power (kW): Constant | 52 | 49 | 47 | 46 | 64 | 60 | 58 | 56 | 85 | 79 | 75 | 73 |
| APU power (kW) | 56 | 52 | 49 | 46 | 58 | 53 | 50 | 48 | 62 | 56 | 53 | 50 |
| Generator power (kW) | 54 | 50 | 48 | 45 | 56 | 51 | 48 | 47 | 59 | 54 | 51 | 49 |
| Battery power (kW) | 33 | 30 | 28 | 27 | 51 | 46 | 43 | 42 | 84 | 75 | 70 | 67 |
| Battery energy (kWh) | 2.9 | 2.7 | 2.5 | 2.3 | 4.4 | 4.1 | 3.8 | 3.6 | 7.3 | 6.7 | 6.1 | 5.8 |
| Battery mass (kg) | 66 | 58 | 51 | 47 | 102 | 89 | 79 | 73 | 168 | 144 | 128 | 117 |
| Total vehicle mass (kg) | 1,386 | 1,341 | 1,310 | 1,281 | 1,457 | 1,401 | 1,364 | 1,336 | 1,591 | 1,513 | 1,465 | 1,426 |
| Acceleration time 0-60 mph (s) | 12.0 | 12.0 | 12.0 | 12.0 | 10.0 | 10.0 | 10.0 | 10.0 | 8.0 | 8.0 | 8.0 | 8.0 |
| Estimated all-elec range (mi) | 5 | 5 | 5 | 5 | 8 | 8 | 8 | 8 | 14 | 13 | 12 | 13 |

Series Grid-independent FHV: HEVCOST Model Run with ADVISOR mpg (for CV & HEV) dated 12/1/99. The battery life increased to last the life of HEV.

Run date: 3/30/2000

**Argonne National Laboratory: Center for Transportation Research**

**A Methodology for Projecting Parallel Hybrid Electric Vehicle Cost**

**(All costs are in 1995 dollars. Battery costs are based on the ANL Delphi study.)**

**HEVTECA (Parallel, Grid-Connected, UL Steel, Intermediate Batt, 12-16s All-electric) ADVISOR-2 Components Matching**

| | Vehicle type: **Midsize Car**<br>All-electric Z60 Time: **16 seconds**<br>Battery type: **NiMH (Intermediate)** | | | | Vehicle type: **Midsize Car**<br>All-electric Z60 Time: **14 seconds**<br>Battery type: **NiMH (Intermediate)** | | | | Vehicle type: **Midsize Car**<br>All-electric Z60 Time: **12 seconds**<br>Battery type: **NiMH (Intermediate)** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Item** | **2005** | **2010** | **2015** | **2020** | **2005** | **2010** | **2015** | **2020** | **2005** | **2010** | **2015** | **2020** |
| | **Purchase Price** | | | | **Purchase Price** | | | | **Purchase Price** | | | |
| **Conventional Vehicle** | $ 23,700 | $ 23,700 | $ 23,700 | $ 23,600 | $ 24,300 | $ 24,300 | $ 24,300 | $ 24,300 | $ 25,000 | $ 25,000 | $ 25,000 | $ 25,000 |
| **Hybrid Electric Vehicle** | | | | | | | | | | | | |
| Common components | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 |
| Additional aluminum cost | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - |
| Auxiliary Power Unit | $ 3,170 | $ 3,180 | $ 3,240 | $ 3,340 | $ 3,220 | $ 3,230 | $ 3,290 | $ 3,400 | $ 3,310 | $ 3,280 | $ 3,390 | $ 3,510 |
| Generator | $ 740 | $ 630 | $ 570 | $ 550 | $ 740 | $ 630 | $ 590 | $ 550 | $ 760 | $ 630 | $ 590 | $ 570 |
| Inverter & Power Electronics | $ 3,200 | $ 2,410 | $ 1,910 | $ 1,640 | $ 3,670 | $ 2,720 | $ 2,130 | $ 1,820 | $ 4,320 | $ 3,180 | $ 2,490 | $ 2,110 |
| Motor | $ 1,810 | $ 1,440 | $ 1,250 | $ 1,160 | $ 2,090 | $ 1,640 | $ 1,410 | $ 1,310 | $ 2,470 | $ 1,950 | $ 1,660 | $ 1,540 |
| Transmission | $ 1,290 | $ 1,190 | $ 1,160 | $ 1,130 | $ 1,410 | $ 1,300 | $ 1,260 | $ 1,230 | $ 1,580 | $ 1,460 | $ 1,420 | $ 1,390 |
| System control | $ 420 | $ 410 | $ 390 | $ 350 | $ 420 | $ 410 | $ 390 | $ 350 | $ 420 | $ 410 | $ 390 | $ 350 |
| Other body parts | $ 400 | $ 390 | $ 380 | $ 370 | $ 400 | $ 390 | $ 380 | $ 370 | $ 400 | $ 390 | $ 380 | $ 370 |
| Additional HVAC Cost | $ 120 | $ 110 | $ 110 | $ 110 | $ 120 | $ 110 | $ 110 | $ 110 | $ 120 | $ 110 | $ 110 | $ 110 |
| First Battery Price | $ 7,520 | $ 6,010 | $ 5,350 | $ 4,820 | $ 8,960 | $ 7,080 | $ 6,250 | $ 5,580 | $ 10,950 | $ 8,630 | $ 7,700 | $ 6,850 |
| Total HEV Price | $ 34,940 | $ 32,040 | $ 30,630 | $ 29,740 | $ 37,300 | $ 33,780 | $ 32,080 | $ 30,990 | $ 40,600 | $ 36,310 | $ 34,400 | $ 33,070 |
| | **Operating Cost** | | | | **Operating Cost** | | | | **Operating Cost** | | | |
| **Conventional Vehicle** | | | | | | | | | | | | |
| Fuel cost (c/mi) | 5.33 | 5.34 | 5.32 | 5.22 | 5.60 | 5.59 | 5.55 | 5.42 | 5.95 | 5.91 | 5.83 | 5.66 |
| Non-fuel cost (c/mi) | 4.90 | 4.97 | 5.05 | 5.20 | 4.90 | 4.97 | 5.05 | 5.20 | 4.90 | 4.97 | 5.05 | 5.20 |
| Total cost (c/mi) | 10.23 | 10.32 | 10.37 | 10.42 | 10.50 | 10.57 | 10.59 | 10.62 | 10.85 | 10.89 | 10.88 | 10.86 |
| **Hybrid Electric Vehicle** | | | | | | | | | | | | |
| Electricity cost (c/mi) | 0.93 | 0.88 | 0.84 | 0.80 | 1.11 | 1.03 | 0.98 | 0.95 | 1.36 | 1.26 | 1.20 | 1.17 |
| Fuel cost (c/mi) | 1.84 | 1.76 | 1.70 | 1.65 | 1.63 | 1.56 | 1.51 | 1.46 | 1.38 | 1.30 | 1.26 | 1.21 |
| Non-fuel cost (c/mi) | 5.55 | 5.63 | 5.72 | 5.89 | 5.55 | 5.63 | 5.72 | 5.89 | 5.55 | 5.63 | 5.72 | 5.89 |
| Battery cost (c/mi) | 12.15 | 9.31 | 7.93 | 7.16 | 14.47 | 10.97 | 9.27 | 8.29 | 17.69 | 13.37 | 11.42 | 10.18 |
| Total cost (c/mi) | 20.47 | 17.58 | 16.19 | 15.51 | 22.77 | 19.20 | 17.48 | 16.59 | 25.97 | 21.56 | 19.60 | 18.45 |
| | **Life-cycle Cost** | | | | **Life-cycle Cost** | | | | **Life-cycle Cost** | | | |
| **Conventional Vehicle** | | | | | | | | | | | | |
| Purchase Price (c/mi) | 23.26 | 22.91 | 22.58 | 22.49 | 23.85 | 23.49 | 23.15 | 23.15 | 24.53 | 24.17 | 23.82 | 23.82 |
| Operating Cost (c/mi) | 10.23 | 10.32 | 10.37 | 10.42 | 10.50 | 10.57 | 10.59 | 10.62 | 10.85 | 10.89 | 10.88 | 10.86 |
| Less Scrappage Value (c/mi) | (0.15) | (0.14) | (0.14) | (0.14) | (0.15) | (0.15) | (0.14) | (0.14) | (0.15) | (0.15) | (0.15) | (0.15) |
| Total Life-cycle Cost (c/mi) | 33.34 | 33.09 | 32.81 | 32.76 | 34.20 | 33.91 | 33.60 | 33.63 | 35.23 | 34.91 | 34.55 | 34.54 |
| **Hybrid Electric Vehicle** | | | | | | | | | | | | |
| Purchase Price - Battery (c/mi) | 26.91 | 25.16 | 24.09 | 23.74 | 27.81 | 25.81 | 24.61 | 24.21 | 29.10 | 26.76 | 25.44 | 24.98 |
| Operating Cost (c/mi) | 20.47 | 17.58 | 16.19 | 15.51 | 22.77 | 19.20 | 17.48 | 16.59 | 25.97 | 21.56 | 19.60 | 18.45 |
| Less Scrappage Value (c/mi) | (0.17) | (0.16) | (0.15) | (0.15) | (0.17) | (0.16) | (0.15) | (0.15) | (0.18) | (0.17) | (0.16) | (0.15) |
| Total Life-cycle Cost (c/mi) | 47.21 | 42.59 | 40.12 | 39.10 | 50.40 | 44.85 | 41.94 | 40.66 | 54.89 | 48.16 | 44.88 | 43.28 |
| | **Important HEV Parameters** | | | | **Important HEV Parameters** | | | | **Important HEV Parameters** | | | |
| Motor power (kW): Peak | 59 | 55 | 54 | 52 | 70 | 65 | 63 | 61 | 85 | 80 | 77 | 75 |
| Motor power (kW): Constant | 41 | 38 | 37 | 36 | 48 | 45 | 43 | 42 | 58 | 55 | 53 | 51 |
| APU power (kW) | 51 | 48 | 46 | 45 | 52 | 49 | 47 | 46 | 54 | 50 | 49 | 48 |
| Generator power (kW) | 17 | 16 | 15 | 15 | 17 | 16 | 16 | 15 | 18 | 16 | 16 | 16 |
| Battery power (kW) | 68 | 62 | 59 | 57 | 81 | 73 | 69 | 66 | 99 | 89 | 85 | 81 |
| Battery energy (kWh) | 9.9 | 9.2 | 8.6 | 8.2 | 11.8 | 10.9 | 10.1 | 9.5 | 14.4 | 13.2 | 12.5 | 11.7 |
| Battery mass (kg) | 202 | 177 | 160 | 148 | 241 | 209 | 188 | 171 | 294 | 255 | 231 | 210 |
| Total vehicle mass (kg) | 1,495 | 1,441 | 1,404 | 1,374 | 1,556 | 1,494 | 1,451 | 1,417 | 1,647 | 1,570 | 1,527 | 1,488 |
| Accl time on APU+Battery (s) | 9.1 | 9.1 | 9.1 | 9.2 | 8.6 | 8.6 | 8.7 | 8.7 | 8.1 | 8.1 | 8.1 | 8.1 |
| Accl time on Battery-only (s) | 16.0 | 16.0 | 16.0 | 16.0 | 14.0 | 14.0 | 14.0 | 14.0 | 12.0 | 12.0 | 12.0 | 12.0 |
| Estimated all-elec range (mi) | 22.7 | 23.2 | 22.4 | 21.8 | 25.9 | 26.3 | 25.4 | 24.3 | 30.0 | 30.5 | 29.7 | 28.1 |

Parallel Grid-Connected FHV: HEVCOST Model Run with ADVISOR mpg (for CV & HEV) dated 12/10/99. The default battery life used, requires one battery replacement.

Run date: 3/30/2000

### Argonne National Laboratory: Center for Transportation Research
### A Methodology for Projecting Parallel Hybrid Electric Vehicle Cost
**(All costs are in 1995 dollars. Battery costs are based on the ANL Delphi study.)**

**HEVTECA (Parallel, Grid-Connected, UL Steel, Int Batt Lasts Veh Life, 12-16s All-electric) ADVISOR-2 Components Matching**

| | Vehicle type: **Midsize Car**<br>All-electric Z60 Time: **16 seconds**<br>Battery type: **NiMH (Intermediate)** | | | | Vehicle type: **Midsize Car**<br>All-electric Z60 Time: **14 seconds**<br>Battery type: **NiMH (Intermediate)** | | | | Vehicle type: **Midsize Car**<br>All-electric Z60 Time: **12 seconds**<br>Battery type: **NiMH (Intermediate)** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Item** | **2005** | **2010** | **2015** | **2020** | **2005** | **2010** | **2015** | **2020** | **2005** | **2010** | **2015** | **2020** |
| | **Purchase Price** | | | | **Purchase Price** | | | | **Purchase Price** | | | |
| **Conventional Vehicle** | $ 23,700 | $ 23,700 | $ 23,700 | $ 23,600 | $ 24,300 | $ 24,300 | $ 24,300 | $ 24,300 | $ 25,000 | $ 25,000 | $ 25,000 | $ 25,000 |
| **Hybrid Electric Vehicle** | | | | | | | | | | | | |
| Common components | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 |
| Additional aluminum cost | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - |
| Auxiliary Power Unit | $ 3,170 | $ 3,180 | $ 3,240 | $ 3,340 | $ 3,220 | $ 3,230 | $ 3,290 | $ 3,400 | $ 3,310 | $ 3,280 | $ 3,390 | $ 3,510 |
| Generator | $ 740 | $ 630 | $ 570 | $ 550 | $ 740 | $ 630 | $ 590 | $ 550 | $ 760 | $ 630 | $ 590 | $ 570 |
| Inverter & Power Electronics | $ 3,200 | $ 2,410 | $ 1,910 | $ 1,640 | $ 3,670 | $ 2,720 | $ 2,130 | $ 1,820 | $ 4,320 | $ 3,180 | $ 2,490 | $ 2,110 |
| Motor | $ 1,810 | $ 1,440 | $ 1,250 | $ 1,160 | $ 2,090 | $ 1,640 | $ 1,410 | $ 1,310 | $ 2,470 | $ 1,950 | $ 1,660 | $ 1,540 |
| Transmission | $ 1,290 | $ 1,190 | $ 1,160 | $ 1,130 | $ 1,410 | $ 1,300 | $ 1,260 | $ 1,230 | $ 1,580 | $ 1,460 | $ 1,420 | $ 1,390 |
| System control | $ 420 | $ 410 | $ 390 | $ 350 | $ 420 | $ 410 | $ 390 | $ 350 | $ 420 | $ 410 | $ 390 | $ 350 |
| Other body parts | $ 400 | $ 390 | $ 380 | $ 370 | $ 400 | $ 390 | $ 380 | $ 370 | $ 400 | $ 390 | $ 380 | $ 370 |
| Additional HVAC Cost | $ 120 | $ 110 | $ 110 | $ 110 | $ 120 | $ 110 | $ 110 | $ 110 | $ 120 | $ 110 | $ 110 | $ 110 |
| First Battery Price | $ 7,520 | $ 6,010 | $ 5,350 | $ 4,820 | $ 8,960 | $ 7,080 | $ 6,250 | $ 5,580 | $ 10,950 | $ 8,630 | $ 7,700 | $ 6,850 |
| Total HEV Price | $ 34,940 | $ 32,040 | $ 30,630 | $ 29,740 | $ 37,300 | $ 33,780 | $ 32,080 | $ 30,990 | $ 40,600 | $ 36,310 | $ 34,400 | $ 33,070 |
| | **Operating Cost** | | | | **Operating Cost** | | | | **Operating Cost** | | | |
| **Conventional Vehicle** | | | | | | | | | | | | |
| Fuel cost (c/mi) | 5.33 | 5.34 | 5.32 | 5.22 | 5.60 | 5.59 | 5.55 | 5.42 | 5.95 | 5.91 | 5.83 | 5.66 |
| Non-fuel cost (c/mi) | 4.90 | 4.97 | 5.05 | 5.20 | 4.90 | 4.97 | 5.05 | 5.20 | 4.90 | 4.97 | 5.05 | 5.20 |
| Total cost (c/mi) | 10.23 | 10.32 | 10.37 | 10.42 | 10.50 | 10.57 | 10.59 | 10.62 | 10.85 | 10.89 | 10.88 | 10.86 |
| **Hybrid Electric Vehicle** | | | | | | | | | | | | |
| Electricity cost (c/mi) | 0.93 | 0.88 | 0.84 | 0.80 | 1.11 | 1.03 | 0.98 | 0.95 | 1.36 | 1.26 | 1.20 | 1.17 |
| Fuel cost (c/mi) | 1.84 | 1.76 | 1.70 | 1.65 | 1.63 | 1.56 | 1.51 | 1.46 | 1.38 | 1.30 | 1.26 | 1.21 |
| Non-fuel cost (c/mi) | 5.55 | 5.63 | 5.72 | 5.89 | 5.55 | 5.63 | 5.72 | 5.89 | 5.55 | 5.63 | 5.72 | 5.89 |
| Battery cost (c/mi) | 7.38 | 5.81 | 5.10 | 4.59 | 8.79 | 6.84 | 5.95 | 5.32 | 10.75 | 8.34 | 7.34 | 6.53 |
| Total cost (c/mi) | 15.70 | 14.08 | 13.35 | 12.94 | 17.08 | 15.07 | 14.17 | 13.62 | 19.03 | 16.54 | 15.51 | 14.80 |
| | **Life-cycle Cost** | | | | **Life-cycle Cost** | | | | **Life-cycle Cost** | | | |
| **Conventional Vehicle** | | | | | | | | | | | | |
| Purchase Price (c/mi) | 23.26 | 22.91 | 22.58 | 22.49 | 23.85 | 23.49 | 23.15 | 23.15 | 24.53 | 24.17 | 23.82 | 23.82 |
| Operating Cost (c/mi) | 10.23 | 10.32 | 10.37 | 10.42 | 10.50 | 10.57 | 10.59 | 10.62 | 10.85 | 10.89 | 10.88 | 10.86 |
| Less Scrappage Value (c/mi) | (0.15) | (0.14) | (0.14) | (0.14) | (0.15) | (0.15) | (0.14) | (0.14) | (0.15) | (0.15) | (0.15) | (0.15) |
| Total Life-cycle Cost (c/mi) | 33.34 | 33.09 | 32.81 | 32.76 | 34.20 | 33.91 | 33.60 | 33.63 | 35.23 | 34.91 | 34.55 | 34.54 |
| **Hybrid Electric Vehicle** | | | | | | | | | | | | |
| Purchase Price - Battery (c/mi) | 26.91 | 25.16 | 24.09 | 23.74 | 27.81 | 25.81 | 24.61 | 24.21 | 29.10 | 26.76 | 25.44 | 24.98 |
| Operating Cost (c/mi) | 15.70 | 14.08 | 13.35 | 12.94 | 17.08 | 15.07 | 14.17 | 13.62 | 19.03 | 16.54 | 15.51 | 14.80 |
| Less Scrappage Value (c/mi) | (0.17) | (0.16) | (0.15) | (0.15) | (0.17) | (0.16) | (0.15) | (0.15) | (0.18) | (0.17) | (0.16) | (0.15) |
| Total Life-cycle Cost (c/mi) | 42.44 | 39.09 | 37.29 | 36.53 | 44.72 | 40.73 | 38.62 | 37.68 | 47.94 | 43.13 | 40.79 | 39.63 |
| | **Important HEV Parameters** | | | | **Important HEV Parameters** | | | | **Important HEV Parameters** | | | |
| Motor power (kW): Peak | 59 | 55 | 54 | 52 | 70 | 65 | 63 | 61 | 85 | 80 | 77 | 75 |
| Motor power (kW): Constant | 41 | 38 | 37 | 36 | 48 | 45 | 43 | 42 | 58 | 55 | 53 | 51 |
| APU power (kW) | 51 | 48 | 46 | 45 | 52 | 49 | 47 | 46 | 54 | 50 | 49 | 48 |
| Generator power (kW) | 17 | 16 | 15 | 15 | 17 | 16 | 16 | 15 | 18 | 16 | 16 | 16 |
| Battery power (kW) | 68 | 62 | 59 | 57 | 81 | 73 | 69 | 66 | 99 | 89 | 85 | 81 |
| Battery energy (kWh) | 9.9 | 9.2 | 8.6 | 8.2 | 11.8 | 10.9 | 10.1 | 9.5 | 14.4 | 13.2 | 12.5 | 11.7 |
| Battery mass (kg) | 202 | 177 | 160 | 148 | 241 | 209 | 188 | 171 | 294 | 255 | 231 | 210 |
| Total vehicle mass (kg) | 1,495 | 1,441 | 1,404 | 1,374 | 1,556 | 1,494 | 1,451 | 1,417 | 1,647 | 1,570 | 1,527 | 1,488 |
| Accl time on APU+Battery (s) | 9.1 | 9.1 | 9.1 | 9.2 | 8.6 | 8.6 | 8.7 | 8.7 | 8.1 | 8.1 | 8.1 | 8.1 |
| Accl time on Battery-only (s) | 16.0 | 16.0 | 16.0 | 16.0 | 14.0 | 14.0 | 14.0 | 14.0 | 12.0 | 12.0 | 12.0 | 12.0 |
| Estimated all-elec range (mi) | 22.7 | 23.2 | 22.4 | 21.8 | 25.9 | 26.3 | 25.4 | 24.3 | 30.0 | 30.5 | 29.7 | 28.1 |

Parallel Grid-Connected FHV: HEVCOST Model Run with ADVISOR mpg (for CV & HEV) dated 12/10/99. The battery life increased to last the life of HEV.
Run date: 3/30/2000

**Argonne National Laboratory: Center for Transportation Research**

**A Methodology for Projecting Series Hybrid Electric Vehicle Cost**

**(All costs are in 1995 dollars. Battery costs are based on the ANL Delphi study.)**

**HEV (Series, Grid-Connected, UL Steel, Int Batt, 12-16s All-electric) ADVISOR2 Components Matching**

| | Vehicle type: **Midsize Car** | | | | Vehicle type: **Midsize Car** | | | | Vehicle type: **Midsize Car** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | All-electric Z60 Time: **16 seconds** | | | | All-electric Z60 Time: **14 seconds** | | | | All-electric Z60 Time: **12 seconds** | | | |
| | Battery type: **NiMH (Intermediate)** | | | | Battery type: **NiMH (Intermediate)** | | | | Battery type: **NiMH (Intermediate)** | | | |
| **Item** | **2005** | **2010** | **2015** | **2020** | **2005** | **2010** | **2015** | **2020** | **2005** | **2010** | **2015** | **2020** |
| | **Purchase Price** | | | | **Purchase Price** | | | | **Purchase Price** | | | |
| **Conventional Vehicle** | $ 21,200 | $ 21,100 | $ 21,100 | $ 21,100 | $ 21,300 | $ 21,100 | $ 21,100 | $ 21,100 | $ 21,800 | $ 21,900 | $ 21,600 | $ 21,600 |
| **Hybrid Electric Vehicle** | | | | | | | | | | | | |
| Common components | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 |
| Additional aluminum cost | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - |
| Auxiliary Power Unit | $ 3,600 | $ 3,530 | $ 3,550 | $ 3,620 | $ 3,650 | $ 3,580 | $ 3,600 | $ 3,620 | $ 3,690 | $ 3,630 | $ 3,650 | $ 3,670 |
| Generator | $ 1,760 | $ 1,390 | $ 1,180 | $ 1,110 | $ 1,780 | $ 1,410 | $ 1,200 | $ 1,110 | $ 1,810 | $ 1,440 | $ 1,220 | $ 1,130 |
| Inverter & Power Electronics | $ 3,600 | $ 2,640 | $ 2,200 | $ 1,890 | $ 3,670 | $ 2,690 | $ 2,220 | $ 1,910 | $ 3,780 | $ 2,810 | $ 2,270 | $ 1,950 |
| Motor | $ 2,320 | $ 1,740 | $ 1,570 | $ 1,460 | $ 2,370 | $ 1,780 | $ 1,590 | $ 1,480 | $ 2,450 | $ 1,870 | $ 1,620 | $ 1,510 |
| Transmission | $ 510 | $ 430 | $ 430 | $ 410 | $ 520 | $ 440 | $ 430 | $ 420 | $ 530 | $ 460 | $ 440 | $ 430 |
| System control | $ 420 | $ 410 | $ 390 | $ 350 | $ 420 | $ 410 | $ 390 | $ 350 | $ 420 | $ 410 | $ 390 | $ 350 |
| Other body parts | $ 400 | $ 390 | $ 380 | $ 370 | $ 400 | $ 390 | $ 380 | $ 370 | $ 400 | $ 390 | $ 380 | $ 370 |
| Additional HVAC Cost | $ 120 | $ 110 | $ 110 | $ 110 | $ 120 | $ 110 | $ 110 | $ 110 | $ 120 | $ 110 | $ 110 | $ 110 |
| First Battery Price | $ 7,410 | $ 5,820 | $ 5,170 | $ 4,650 | $ 8,630 | $ 6,790 | $ 6,070 | $ 5,410 | $ 10,400 | $ 8,240 | $ 7,250 | $ 6,510 |
| Total HEV Price | $ 36,500 | $ 32,800 | $ 31,300 | $ 30,300 | $ 37,900 | $ 33,900 | $ 32,300 | $ 31,100 | $ 39,900 | $ 35,700 | $ 33,600 | $ 32,300 |
| | **Operating Cost** | | | | **Operating Cost** | | | | **Operating Cost** | | | |
| **Conventional Vehicle** | | | | | | | | | | | | |
| Fuel cost (c/mi) | 4.25 | 4.20 | 4.20 | 4.14 | 4.27 | 4.22 | 4.19 | 4.13 | 4.51 | 4.56 | 4.45 | 4.40 |
| Non-fuel cost (c/mi) | 4.90 | 4.97 | 5.05 | 5.20 | 4.90 | 4.97 | 5.05 | 5.20 | 4.90 | 4.97 | 5.05 | 5.20 |
| Total cost (c/mi) | 9.15 | 9.17 | 9.25 | 9.34 | 9.17 | 9.19 | 9.24 | 9.33 | 9.41 | 9.53 | 9.50 | 9.60 |
| **Hybrid Electric Vehicle** | | | | | | | | | | | | |
| Electricity cost (c/mi) | 0.92 | 0.85 | 0.81 | 0.77 | 1.07 | 0.99 | 0.94 | 0.89 | 1.29 | 1.20 | 1.13 | 1.07 |
| Fuel cost (c/mi) | 2.09 | 2.03 | 1.97 | 1.91 | 1.88 | 1.82 | 1.77 | 1.71 | 1.60 | 1.52 | 1.48 | 1.43 |
| Non-fuel cost (c/mi) | 5.55 | 5.63 | 5.72 | 5.89 | 5.55 | 5.63 | 5.72 | 5.89 | 5.55 | 5.63 | 5.72 | 5.89 |
| Battery cost (c/mi) | 11.97 | 9.01 | 7.66 | 6.91 | 13.94 | 10.52 | 9.00 | 8.04 | 16.80 | 12.77 | 10.75 | 9.67 |
| Total cost (c/mi) | 20.53 | 17.53 | 16.16 | 15.47 | 22.44 | 18.96 | 17.43 | 16.53 | 25.23 | 21.12 | 19.08 | 18.06 |
| | **Life-cycle Cost** | | | | **Life-cycle Cost** | | | | **Life-cycle Cost** | | | |
| **Conventional Vehicle** | | | | | | | | | | | | |
| Purchase Price (c/mi) | 20.80 | 20.40 | 20.10 | 20.10 | 20.90 | 20.40 | 20.10 | 20.10 | 21.39 | 21.17 | 20.58 | 20.58 |
| Operating Cost (c/mi) | 9.15 | 9.17 | 9.25 | 9.34 | 9.17 | 9.19 | 9.24 | 9.33 | 9.41 | 9.53 | 9.50 | 9.60 |
| Less Scrappage Value (c/mi) | (0.13) | (0.13) | (0.12) | (0.12) | (0.13) | (0.13) | (0.12) | (0.12) | (0.13) | (0.13) | (0.13) | (0.13) |
| Total Life-cycle Cost (c/mi) | 29.83 | 29.44 | 29.23 | 29.32 | 29.94 | 29.47 | 29.22 | 29.31 | 30.67 | 30.57 | 29.95 | 30.05 |
| **Hybrid Electric Vehicle** | | | | | | | | | | | | |
| Purchase Price - Battery (c/mi) | 28.55 | 26.08 | 24.90 | 24.44 | 28.72 | 26.21 | 24.99 | 24.48 | 28.95 | 26.55 | 25.11 | 24.57 |
| Operating Cost (c/mi) | 20.53 | 17.53 | 16.16 | 15.47 | 22.44 | 18.96 | 17.43 | 16.53 | 25.23 | 21.12 | 19.08 | 18.06 |
| Less Scrappage Value (c/mi) | (0.18) | (0.16) | (0.15) | (0.15) | (0.18) | (0.16) | (0.15) | (0.15) | (0.18) | (0.17) | (0.15) | (0.15) |
| Total Life-cycle Cost (c/mi) | 48.89 | 43.45 | 40.90 | 39.76 | 50.98 | 45.01 | 42.27 | 40.86 | 54.00 | 47.50 | 44.03 | 42.48 |
| | **Important HEV Parameters** | | | | **Important HEV Parameters** | | | | **Important HEV Parameters** | | | |
| Motor power (kW): Peak | 79 | 70 | 72 | 70 | 81 | 72 | 73 | 71 | 84 | 76 | 75 | 73 |
| Motor power (kW): Constant | 54 | 48 | 49 | 48 | 56 | 49 | 50 | 49 | 58 | 52 | 51 | 50 |
| APU power (kW) | 60 | 55 | 52 | 50 | 61 | 56 | 53 | 50 | 62 | 57 | 54 | 51 |
| Generator power (kW) | 57 | 53 | 50 | 49 | 58 | 54 | 51 | 49 | 59 | 55 | 52 | 50 |
| Battery power (kW) | 67 | 60 | 57 | 55 | 78 | 70 | 67 | 64 | 94 | 85 | 80 | 77 |
| Battery energy (kWh) | 9.7 | 8.9 | 8.4 | 7.9 | 11.3 | 10.4 | 9.8 | 9.3 | 13.7 | 12.6 | 11.7 | 11.1 |
| Battery mass (kg) | 199 | 172 | 155 | 143 | 232 | 200 | 182 | 166 | 280 | 243 | 218 | 200 |
| Total vehicle mass (kg) | 1,538 | 1,464 | 1,429 | 1,395 | 1,577 | 1,500 | 1,461 | 1,419 | 1,634 | 1,554 | 1,503 | 1,459 |
| Accl Time on APU+Battery (s) | 12.0 | 12.3 | 12.3 | 12.2 | 12.0 | 12.2 | 12.3 | 12.3 | 11.1 | 11.1 | 11.4 | 11.4 |
| Accl Time on Battery-only (s) | 16.0 | 16.0 | 16.0 | 16.0 | 14.0 | 14.0 | 14.0 | 14.0 | 12.0 | 12.0 | 12.0 | 12.0 |
| Estimated all-elec range (mi) | 20.9 | 21.1 | 20.4 | 20.1 | 23.7 | 24.0 | 23.5 | 23.0 | 27.6 | 28.2 | 27.3 | 26.9 |

Series Grid-Connected FHV: HEVCOST Model Run with ADVISOR mpg (for CV & HEV) dated 12/10/99. The default battery life used, requires one battery replacement.

Run date: 3/31/2000

**Argonne National Laboratory: Center for Transportation Research**
**A Methodology for Projecting Series Hybrid Electric Vehicle Cost**
**(All costs are in 1995 dollars. Battery costs are based on the ANL Delphi study.)**

**HEV (Series, Grid-Connected, UL Steel, Int Batt Lasts Veh Life, 12-16s All-electric) ADVISOR2 Components Matching**

| | Vehicle type: **Midsize Car**<br>All-electric Z60 Time: **16 seconds**<br>Battery type: **NiMH (Intermediate)** | | | | Vehicle type: **Midsize Car**<br>All-electric Z60 Time: **14 seconds**<br>Battery type: **NiMH (Intermediate)** | | | | Vehicle type: **Midsize Car**<br>All-electric Z60 Time: **12 seconds**<br>Battery type: **NiMH (Intermediate)** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Item** | **2005** | **2010** | **2015** | **2020** | **2005** | **2010** | **2015** | **2020** | **2005** | **2010** | **2015** | **2020** |
| | **Purchase Price** | | | | **Purchase Price** | | | | **Purchase Price** | | | |
| **Conventional Vehicle** | $ 21,200 | $ 21,100 | $ 21,100 | $ 21,100 | $ 21,300 | $ 21,100 | $ 21,100 | $ 21,100 | $ 21,800 | $ 21,900 | $ 21,600 | $ 21,600 |
| **Hybrid Electric Vehicle** | | | | | | | | | | | | |
| Common components | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 | $ 16,270 |
| Additional aluminum cost | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - |
| Auxiliary Power Unit | $ 3,600 | $ 3,530 | $ 3,550 | $ 3,620 | $ 3,650 | $ 3,580 | $ 3,600 | $ 3,620 | $ 3,690 | $ 3,630 | $ 3,650 | $ 3,670 |
| Generator | $ 1,760 | $ 1,390 | $ 1,180 | $ 1,110 | $ 1,780 | $ 1,410 | $ 1,200 | $ 1,110 | $ 1,810 | $ 1,440 | $ 1,220 | $ 1,130 |
| Inverter & Power Electronics | $ 3,600 | $ 2,640 | $ 2,200 | $ 1,890 | $ 3,670 | $ 2,690 | $ 2,220 | $ 1,910 | $ 3,780 | $ 2,810 | $ 2,270 | $ 1,950 |
| Motor | $ 2,320 | $ 1,740 | $ 1,570 | $ 1,460 | $ 2,370 | $ 1,780 | $ 1,590 | $ 1,480 | $ 2,450 | $ 1,870 | $ 1,620 | $ 1,510 |
| Transmission | $ 510 | $ 430 | $ 430 | $ 410 | $ 520 | $ 440 | $ 430 | $ 420 | $ 530 | $ 460 | $ 440 | $ 430 |
| System control | $ 420 | $ 410 | $ 390 | $ 350 | $ 420 | $ 410 | $ 390 | $ 350 | $ 420 | $ 410 | $ 390 | $ 350 |
| Other body parts | $ 400 | $ 390 | $ 380 | $ 370 | $ 400 | $ 390 | $ 380 | $ 370 | $ 400 | $ 390 | $ 380 | $ 370 |
| Additional HVAC Cost | $ 120 | $ 110 | $ 110 | $ 110 | $ 120 | $ 110 | $ 110 | $ 110 | $ 120 | $ 110 | $ 110 | $ 110 |
| First Battery Price | $ 7,410 | $ 5,820 | $ 5,170 | $ 4,650 | $ 8,630 | $ 6,790 | $ 6,070 | $ 5,410 | $ 10,400 | $ 8,240 | $ 7,250 | $ 6,510 |
| Total HEV Price | $ 36,500 | $ 32,800 | $ 31,300 | $ 30,300 | $ 37,900 | $ 33,900 | $ 32,300 | $ 31,100 | $ 39,900 | $ 35,700 | $ 33,600 | $ 32,300 |
| | **Operating Cost** | | | | **Operating Cost** | | | | **Operating Cost** | | | |
| **Conventional Vehicle** | | | | | | | | | | | | |
| Fuel cost (c/mi) | 4.25 | 4.20 | 4.20 | 4.14 | 4.27 | 4.22 | 4.19 | 4.13 | 4.51 | 4.56 | 4.45 | 4.40 |
| Non-fuel cost (c/mi) | 4.90 | 4.97 | 5.05 | 5.20 | 4.90 | 4.97 | 5.05 | 5.20 | 4.90 | 4.97 | 5.05 | 5.20 |
| Total cost (c/mi) | 9.15 | 9.17 | 9.25 | 9.34 | 9.17 | 9.19 | 9.24 | 9.33 | 9.41 | 9.53 | 9.50 | 9.60 |
| **Hybrid Electric Vehicle** | | | | | | | | | | | | |
| Electricity cost (c/mi) | 0.92 | 0.85 | 0.81 | 0.77 | 1.07 | 0.99 | 0.94 | 0.89 | 1.29 | 1.20 | 1.13 | 1.07 |
| Fuel cost (c/mi) | 2.09 | 2.03 | 1.97 | 1.91 | 1.88 | 1.82 | 1.77 | 1.71 | 1.60 | 1.52 | 1.48 | 1.43 |
| Non-fuel cost (c/mi) | 5.55 | 5.63 | 5.72 | 5.89 | 5.55 | 5.63 | 5.72 | 5.89 | 5.55 | 5.63 | 5.72 | 5.89 |
| Battery cost (c/mi) | 7.27 | 5.63 | 4.93 | 4.43 | 8.47 | 6.56 | 5.78 | 5.15 | 10.21 | 7.97 | 6.91 | 6.20 |
| Total cost (c/mi) | 15.82 | 14.14 | 13.42 | 12.99 | 16.97 | 15.01 | 14.21 | 13.65 | 18.64 | 16.32 | 15.24 | 14.59 |
| | **Life-cycle Cost** | | | | **Life-cycle Cost** | | | | **Life-cycle Cost** | | | |
| **Conventional Vehicle** | | | | | | | | | | | | |
| Purchase Price (c/mi) | 20.80 | 20.40 | 20.10 | 20.10 | 20.90 | 20.40 | 20.10 | 20.10 | 21.39 | 21.17 | 20.58 | 20.58 |
| Operating Cost (c/mi) | 9.15 | 9.17 | 9.25 | 9.34 | 9.17 | 9.19 | 9.24 | 9.33 | 9.41 | 9.53 | 9.50 | 9.60 |
| Less Scrappage Value (c/mi) | (0.13) | (0.13) | (0.12) | (0.12) | (0.13) | (0.13) | (0.12) | (0.12) | (0.13) | (0.13) | (0.13) | (0.13) |
| Total Life-cycle Cost (c/mi) | 29.83 | 29.44 | 29.23 | 29.32 | 29.94 | 29.47 | 29.22 | 29.31 | 30.67 | 30.57 | 29.95 | 30.05 |
| **Hybrid Electric Vehicle** | | | | | | | | | | | | |
| Purchase Price - Battery (c/mi) | 28.55 | 26.08 | 24.90 | 24.44 | 28.72 | 26.21 | 24.99 | 24.48 | 28.95 | 26.55 | 25.11 | 24.57 |
| Operating Cost (c/mi) | 15.82 | 14.14 | 13.42 | 12.99 | 16.97 | 15.01 | 14.21 | 13.65 | 18.64 | 16.32 | 15.24 | 14.59 |
| Less Scrappage Value (c/mi) | (0.18) | (0.16) | (0.15) | (0.15) | (0.18) | (0.16) | (0.15) | (0.15) | (0.18) | (0.17) | (0.15) | (0.15) |
| Total Life-cycle Cost (c/mi) | 44.19 | 40.06 | 38.16 | 37.28 | 45.51 | 41.06 | 39.05 | 37.97 | 47.41 | 42.70 | 40.19 | 39.01 |
| | **Important HEV Parameters** | | | | **Important HEV Parameters** | | | | **Important HEV Parameters** | | | |
| Motor power (kW): Peak | 79 | 70 | 72 | 70 | 81 | 72 | 73 | 71 | 84 | 76 | 75 | 73 |
| Motor power (kW): Constant | 54 | 48 | 49 | 48 | 56 | 49 | 50 | 49 | 58 | 52 | 51 | 50 |
| APU power (kW) | 60 | 55 | 52 | 50 | 61 | 56 | 53 | 50 | 62 | 57 | 54 | 51 |
| Generator power (kW) | 57 | 53 | 50 | 49 | 58 | 54 | 51 | 49 | 59 | 55 | 52 | 50 |
| Battery power (kW) | 67 | 60 | 57 | 55 | 78 | 70 | 67 | 64 | 94 | 85 | 80 | 77 |
| Battery energy (kWh) | 9.7 | 8.9 | 8.4 | 7.9 | 11.3 | 10.4 | 9.8 | 9.3 | 13.7 | 12.6 | 11.7 | 11.1 |
| Battery mass (kg) | 199 | 172 | 155 | 143 | 232 | 200 | 182 | 166 | 280 | 243 | 218 | 200 |
| Total vehicle mass (kg) | 1,538 | 1,464 | 1,429 | 1,395 | 1,577 | 1,500 | 1,461 | 1,419 | 1,634 | 1,554 | 1,503 | 1,459 |
| Accl Time on APU+Battery (s) | 12.0 | 12.3 | 12.3 | 12.2 | 12.0 | 12.2 | 12.3 | 12.3 | 11.1 | 11.1 | 11.4 | 11.4 |
| Accl Time on Battery-only (s) | 16.0 | 16.0 | 16.0 | 16.0 | 14.0 | 14.0 | 14.0 | 14.0 | 12.0 | 12.0 | 12.0 | 12.0 |
| Estimated all-elec range (mi) | 20.9 | 21.1 | 20.4 | 20.1 | 23.7 | 24.0 | 23.5 | 23.0 | 27.6 | 28.2 | 27.3 | 26.9 |

Series Grid-Connected FHV: HEVCOST Model Run with ADVISOR mpg (for CV & HEV) dated 12/10/99. The battery life increased to last the life of HEV.

Run date: 3/31/2000

# Section 4 Appendix B
# Reality Check on ADVISOR Results: Highway Cycle Fuel Savings for Parallel Hybrids

The ADVISOR results for the parallel grid-independent hybrids show strong improvements (relative to the conventional drivetrain) in fuel economy on the Highway cycle. For example, among vehicles achieving a 10-second Z60 time, the full hybrid achieves a 21% improvement in fuel economy, and the mild hybrid (MHEV) achieves an 11% improvement. These values appear high in relation to other results we are aware of, though comparisons should be made with caution because of differences in assumptions and vehicle details. For example, OTA's analysis ***of a series hybrid*** yielded an 8-percent improvement on the highway cycle for a Taurus-sized (full) hybrid with 12-second Z60 time (OTA 1995). An (1999) estimated that shifting from a Corolla conventional vehicle to a Prius-like hybrid (which is part series, part parallel) and adjusting for performance yielded about a 4% gain on the Highway cycle. Note, however, that series hybrids should be inferior to parallel hybrids in steady highway driving because of higher electrical losses.

To obtain a better sense of whether the ADVISOR results are plausible, we examined the energy flows and engine efficiency results of the ADVISOR runs in more detail and collected and examined fuel economy test results from a group of vehicles with alternative engine options with different power levels, to examine the effect of engine power on Highway cycle fuel economy.

Table 1 presents key ADVISOR results for the Highway cycle for the vehicles. The results indicate that the Highway mpg improvements increase with increased CV engine displacement and power and with vehicle performance. The mild hybrids appear to obtain more improvement in fuel economy than the full hybrids for each percent reduction in engine power. If correct, this implies diminishing returns as the degree of hybridization increases. Both full and mild hybrids are significantly heavier than the equivalent CV, but there is little weight difference between the two hybrids. This has implications for the fuel economy savings achievable by the hybrids, since added weight yields higher inertia and rolling resistance forces that the vehicles must overcome. However, as we discuss elsewhere, the effects on fuel economy of mass changes are not as great for a hybrid as for a conventional vehicle.

**Table 1 ADVISOR Results for Parallel Grid-Independent ULS Hybrids**

| | 12 seconds | | | 10 seconds | | | 8 seconds | | |
|---|---|---|---|---|---|---|---|---|---|
| Factor | CV | MHEV | FHEV | CV | MHEV | FHEV | CV | MHEV | FHEV |
| Mass, kg | 1175 | 1246 | 1247 | 1248 | 1321 | 1328 | 1366 | 1453 | 1466 |
| Engine power, kW | 66 | 55 | 44 | 85 | 65 | 46 | 116 | 49 | 82 |
| % Power drop | | 17 | 33 | | 24 | 46 | | 29 | 58 |
| Hwy fuel eco, mpg | 47 | 52 | 57 | 42 | 50 | 56 | 35 | 47 | 53 |
| % Fuel eco increase | | 11 | 21 | | 24 | 34 | | 35 | 51 |
| $\Delta$f.e, %/$\Delta$kW, % | | .65 | .64 | | 1.00 | .74 | | 1.21 | .88 |

ADVISOR output includes a list of energy flows through various parts of the drivetrain, e.g., the energy storage system, engine, clutch, motor/controller, gearbox and wheel/axle, etc. Examining these flows during the Highway cycle for the 12-second CV and the pair of parallel grid-independent hybrids yields the following conclusions:

1. The largest part of the HEVs' fuel economy gain comes from increases in engine efficiency, including (according to our interpretation of the ADVISOR accounting system) the effects of idle-off.

2. The engine efficiency gain that comes with reductions in displacement and power is highly nonlinear, so that the gain achieved by the MHEV's reduction from the CV is nearly as great as that achieved by the FHEV, even though the FHEV's power reduction is much greater.

3. Regenerative braking gains for the hybrids are relatively small in the Highway cycle, though there is little difference between the FHEV and MHEV despite the MHEV's smaller motor and battery. This implies that the braking events on the Highway cycle are mild enough that the MHEV's small motor and battery can handle most of them with little need for the mechanical brakes.

4. Losses in the energy storage system are significantly higher in the MHEV than the FHEV. This is not surprising because, with its smaller battery, swings in SOC are wider and more frequent in the MHEV.

The overall implication of these conclusions is that the largest share of energy savings on the Highway cycle will come from increased efficiency of operation of the engine, due to more frequent operation at points of lower fuel consumption. Given the speed profile of the cycle, most of this should come from the effects of engine downsizing and the resulting frequency of operation at a higher fraction of wide open throttle, where this engine technology is most efficient. A small amount also comes from turning the engine off during braking and coasting. Thus, an examination of the fuel economy effects of engine downsizing should then give us a better idea of the realism of the ADVISOR results for the hybrids.

One way of examining the effects of engine downsizing on fuel economy is to examine the fuel economy ratings of car models that offer multiple engine choices. There are a considerable number of vehicles listed in the Fuel Economy Guide with two engine options for the same vehicle. Figure 1 shows a plot of the percentage change in highway mpg versus the percentage change in engine displacement for a number of such vehicles. All the vehicles have manual transmissions (to match the simulated ADVISOR vehicle) and none have four-wheel drive (4WD) or all-wheel drive (AWD). In addition, engine pairs were excluded when it was clear that the pair had substantially different technology, e.g., where only one of the pair was turbocharged. Displacement was used as a proxy for horsepower (which is not given in the guide), which conforms with the scaling routine in ADVISOR.[58] This means that the last row in Table 1, Δf.e,%/ΔkW,%, will be identical to Δf.e,%/Δdisplacement,%.

There are a number of ways to draw the curve of Δf.e,% versus Δdisplacement,%, as shown in the figure. The ratio of averages, which is appealing because it passes through the origin, yields a value of 0.623 for Δf.e,%/Δdisplacement,% and Δf.e,%/ΔkW,%. This matches well with the ADVISOR results for the 12-second vehicles (0.63 for the full hybrid) but not with the results for the faster vehicles. Note, however, that this ratio accounts *only* for engine downsizing, and captures no other effects.

It is not obvious whether or not the net effects of hybridizing, *aside* from engine downsizing, will be positive. These effects are:

- Engine off during idling (only 6 seconds, or less than 1% of the cycle time, on the Highway cycle) and deceleration
- Regenerative braking gains
- Losses in the energy storage system
- Losses associated with added weight

As discussed above, downsizing the engine seems likely to be the primary factor affecting the change in Highway fuel economy when one shifts from a CV to an HEV of equivalent performance. Consequently, the relative similarity between the Δf.e,%/ΔkW,% obtained from ADVISOR and that obtained from the comparison of paired vehicles from the Fuel Economy Guide is reassuring.

[58] This is an approximation, at best.

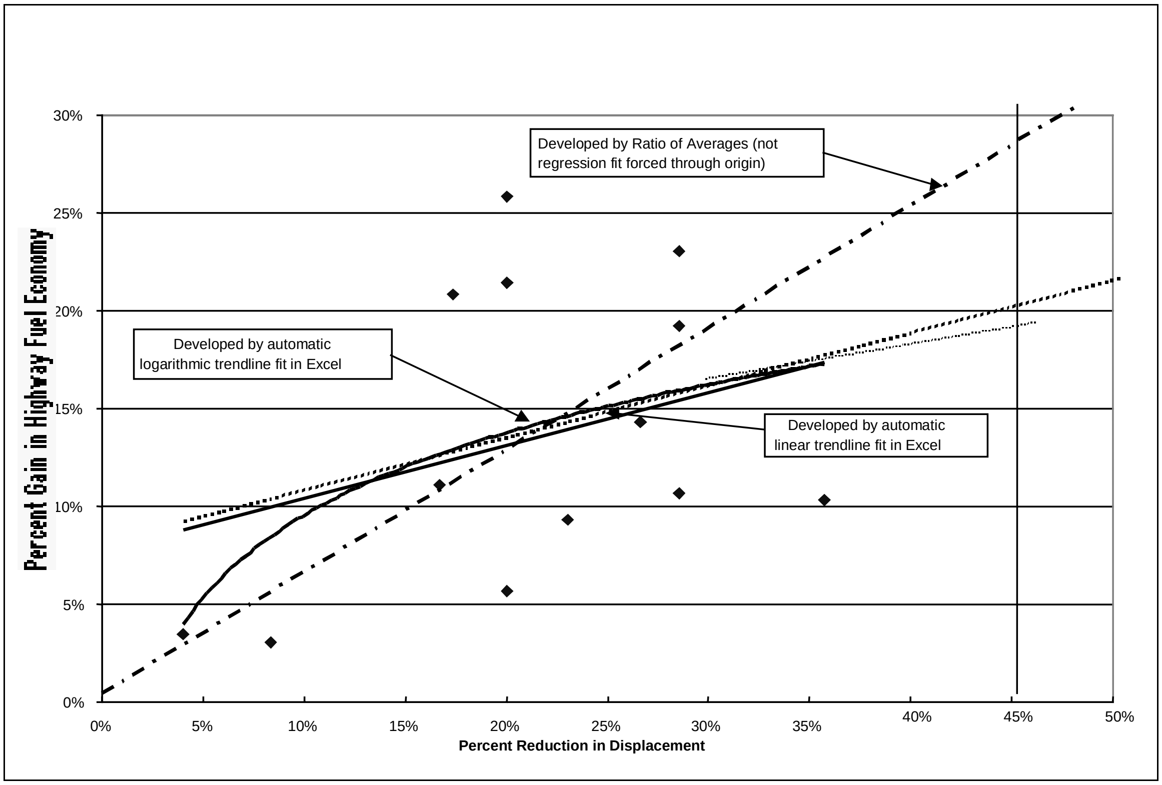



**Figure 1  HWY Cycle Percentage Gain in Fuel Economy as Function of Engine Displacement Reduction**

# Section 4 Appendix C
# Power and Mass Computations for Initial Vehicle Sizing

Hybrid electric vehicles (HEVs) are expected to meet two performance criteria in order to compete successfully with conventional vehicles. The first criterion is the time required to accelerate from zero to 60 mph. The vehicles must also be able to negotiate a minimum grade at a constant speed. Argonne developed a model to compute power requirements associated with these criteria. Each drivetrain component is sized to meet the power requirements and its mass is then computed. The model is described in this section.

## Power Requirements

The procedure presented here estimates power requirements for accelerating on a flat road (no grade) and negotiating a grade represented by an angle θ at a constant speed. We assume that the air is still and vehicles are not required to accelerate from a stop to the maximum speed up a hill or a ramp.

### Acceleration Power

A hybrid vehicle that has an inertia mass of $M_v$ and is accelerating on a flat road (i.e., 0° grade) would require a power $P_a$ specified by the following equation.

$$P_a = M_v v \frac{dv}{dt} + \frac{1}{2}\rho A C_d v^3 + M_v g v C_r \qquad (1)$$

where

$v$ = Vehicle speed,

$\rho$ = Air density,

$A$ = Vehicle frontal area,

$C_d$ = Coefficient of aerodynamic drag,

$g$ = Gravity, and

$C_r$ = Coefficient of rolling resistance.

The power in equation 1 is at the wheels. After the acceleration power is determined, the drivetrain components would be sized to allow for losses at various levels. Since the vehicle is accelerating from a stop to a maximum speed $v_m$, the acceleration power requirements in equation 1 can be restated by integrating the first term from zero to $v_m$.

$$P_a = \frac{M_v}{t_m}\left\{\frac{1}{2}v_m^2 + C_r g\int_0^{t_m} v\,dt\right\} + \frac{\rho A C_d}{2t_m}\int_0^{t_m} v^3\,dt \qquad (2)$$

Where $t_m$ is the time taken to reach the maximum speed.

The speed $v$ in equation 2 is a function of time $t$. Under conditions involving a smooth acceleration, the speed and time relationship can be plotted as shown in Figure 1. Assuming that the vehicle speed and time relationship is approximated by a hyperbolic function, speed v in equation 2 can be expressed as:

$$v = v_m\left(\frac{t}{t_m}\right)^x \qquad (3)$$

The exponent $x$ in the above equation has a value in the range of 0.5-0.66 for zero to 60 mph acceleration (Z60) times of 8-13 seconds.

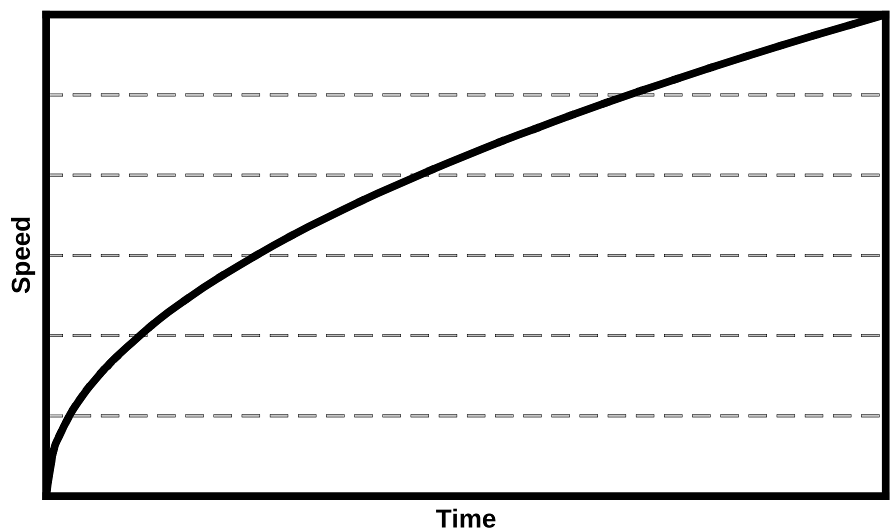



**Figure 1 Vehicle Speed and Time Relationship during Acceleration**

Two approaches were explored for computing the acceleration power requirements: (i) by integrating equation 2, and (ii) by solving the power equation between time $t_m$ and $t_m+0.1$.

The first approach provides an average value for the acceleration power. The integrated equation 2 has two terms. The first term provides the power requirement for moving the vehicle mass and the second term provides the average power required for overcoming air resistance.

The simplified equation for acceleration power $P_a$ can be written as shown below.

$$P_a = a_1 M_v + b_1 \qquad (4)$$

where

$$a_1 = \frac{v_m^2}{2t_m} + \frac{C_r g}{t_m}\int_0^{t_m} v\,dt = \frac{v_m^2}{2t_m} + \frac{1}{1+x}C_r g v_m \tag{5}$$

and

$$b_1 = \frac{\rho A C_d}{2t_m}\int_0^{t_m} v^3 dt = \frac{1}{2(1+2x)}\rho A C_d v_m^3 \tag{6}$$

Equation 4 shows that the acceleration power has two parts: one is linear to vehicle mass and the other is a constant that depends on vehicle design. The term "$a_1$" is a function of acceleration specifications (i.e., maximum speed and time to reach it) and rolling resistance. The term "$b_1$" represents power required to overcome the aerodynamic drag and is a function of drag coefficient and frontal area. The aerodynamic power requirement does not depend on vehicle mass.

The second approach provides an estimate of passing power requirement at the maximum speed $v_m$. Since the vehicle accelerates for only 0.1 seconds, this estimate would be very close to the maximum power required to reach the target speed. This approach would provide a power value higher than the first approach.

Equation 2 is used for this approach. The value of $v$ is $v_m$, here for aerodynamic drag and rolling resistance, the time range is $t_m$ to $t_m+0.1$, and $dt$ has a value of 0.1. The equation can be used in the following form.

$$P_a = M_v v_m \left[ v_m \left( \frac{t_m + 0.1}{t_m} \right)^x - v_m \left( \frac{t_m}{t_m} \right)^x \right] \div 0.1 + \frac{1}{2}\rho A C_d v_m^3 + M_v g v_m C_r \tag{7}$$

$$= M_v \frac{v_m^2}{0.1}\left[ \left( \frac{t_m + 0.1}{t_m} \right)^x - 1 \right] + \frac{1}{2}\rho A C_d v_m^3 + M_v g v_m C_r \tag{8}$$

This equation can be simplified in a form similar to that of equation 4:

$$P_a = aM_v + b \tag{9}$$

where

$$a = \frac{v_m^2}{0.1}\left[ \left( \frac{t_m + 0.1}{t_m} \right)^x - 1 \right] + C_r g v_m \tag{10}$$

$$b = \frac{1}{2} \rho A C_d v_m^3 \tag{11}$$

## Grade-Climbing Power

Power ($P_g$) required for negotiating a grade that is represented by angle θ at a constant speed $v_g$ could be written as follows:

$$P_g = \frac{1}{2} \rho A C_d v_g^3 + M_v g v_g \sin\theta + M_v g v_g C_r \cos\theta \tag{12}$$

This equation can be simplified as:

$$P_g = c M_v + d \tag{13}$$

where

$$c = g v_g \left( \sin\theta + C_r \cos\theta \right) \text{ and} \tag{14}$$

$$d = \frac{1}{2} \rho A C_d v_g^3 \tag{15}$$

The grade-climbing power requirement also has two parts, one linear to vehicle mass and the other a constant dependent on vehicle design. The term *c* represents the effects of grade specifications (i.e., speed and grade angle) and rolling resistance, while the term *d* represents the power required to overcome aerodynamic drag.

Both the acceleration and grade climbing power requirements are dependent on vehicle mass. The acceleration power requirement is usually higher than the grade-climbing power requirement because the inertial forces that must be overcome during rapid acceleration generally will outweigh the weight force of a grade climb (unless the grade is extremely steep). The Partnership for a New Generation of Vehicles (PNGV) has compiled a set of vehicle specifications. Under these specifications a high fuel economy vehicle should accelerate from zero to 60 mph in 12 seconds and should be able to sustain a constant speed of 55 mph for 20 minutes while climbing a 6.5% grade. Figure 2 shows the general relationship between the two power requirements and vehicle mass under these specifications. The gap between the two power requirements increases as vehicle mass increases.

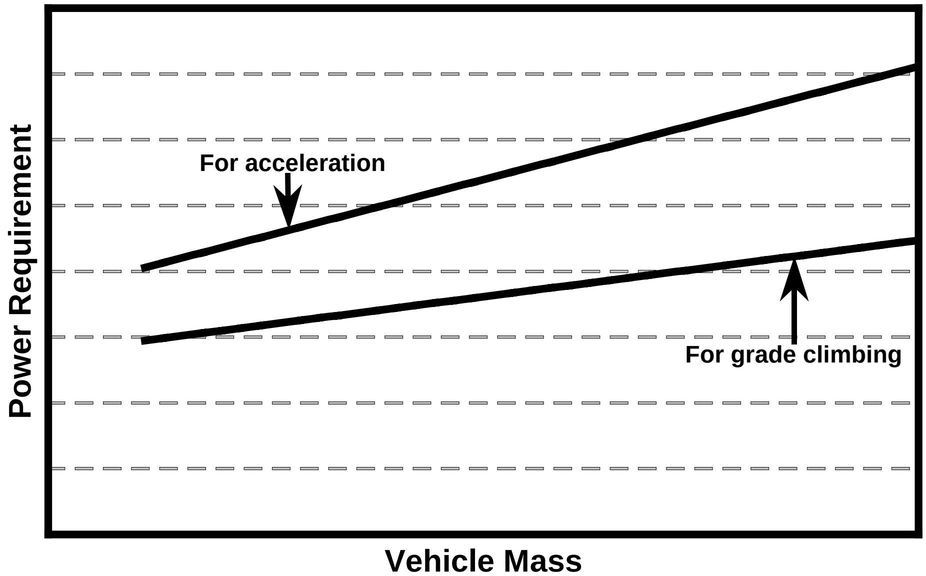



**Figure 2 Power Requirements as a Function of Vehicle Mass**

## Vehicle Mass

A vehicle has three distinct mass groups: (1) body, (2) chassis, and (3) drivetrain. The body and chassis for the hybrid and conventional vehicles would be nearly identical. The conventional vehicle mass and contributions by individual group have been analyzed earlier (Stodolsky et al. 1995a; OTA 1995). Conventional steel vehicles have 73-74% of their total vehicle mass in body and chassis groups. The optimal use of ultralight steel might reduce the total vehicle mass by 10-12% while optimal use of aluminum would reduce the total mass by 31% (Stodolsky et al. 1995b; OTA 1995; AISI 1998). In the case of a hybrid vehicle, a smaller power unit (PU), a motor and an inverter, a generator, a battery pack, and a gear-drive or transmission (depending upon the hybrid design) will replace the conventional engine and transmission.

The total inertia mass $M_v$ is expressed as follows:

$$M_v = M_b + M_{ch} + M_{dt} + M_l \qquad (16)$$

where:

$M_b$ = Body mass,

$M_{ch}$ = Chassis mass,

$M_{dt}$ = Drivetrain mass, and

$M_l$ = Load.

The body and chassis mass, $M_b$ and $M_{ch}$, depend on vehicle design and their sum $M_f$ can be treated as fixed.

The drivetrain has several components, each with its own efficiency and specific power. The efficiency helps determine the power rating for the component, and the specific power determines its mass. The drivetrain mass is specified as:

$$M_{dt} = M_{pu} + M_{bat} + M_{mot} + M_{gen} + M_{tran} \tag{17}$$

where

$M_{pu}$ = PU mass,

$M_{bat}$ = Battery mass,

$M_{mot}$ = Motor and inverter mass,

$M_{gen}$ = Generator mass, and

$M_{tra}$ = Transmission mass.

Let $S_{pu}$, $S_{bat}$, $S_{mot}$, $S_{gen}$, and $S_{tran}$ be the specific power for each of the five components and $P_{pu}$, $P_{bat}$, $P_{mot}$, $P_{gen}$, and $P_{tran}$ be the power ratings. Then mass of each component can be computed as power divided by specific power:

$$M_{pu} = P_{pu}/S_{pu} \tag{18}$$

$$M_{bat} = P_{bat}/S_{bat} \tag{19}$$

$$M_{mot} = P_{mot}/S_{mot} \tag{20}$$

$$M_{gen} = P_{gen}/S_{gen} \tag{21}$$

$$M_{tran} = P_{tran}/S_{tran} \tag{22}$$

These mass and specific power values are for the complete component assembly including auxiliary and/or supporting units. For example, the motor assembly includes the inverter.

## Component Sizing

The acceleration and grade-climbing power estimates from the above described procedure represent power delivered at the wheels. Each component has its own power conversion efficiency and some losses are involved in mechanical components such as bearings. A design factor, *k*, is used to account for other losses and contingencies.

The power rating of a drivetrain component depends upon the HEV system configuration, series or parallel. The motor delivers all the required power through the transmission in a series HEV while both the power unit and motor deliver power through the transmission in a parallel HEV. A series HEV's transmission is simple, consisting of a few reduction gears, while a parallel HEV's transmission is relatively complex, requiring linking of the two power sources. Also, the power unit's link to the drive axle requires greater control compared to the link of a motor. The component sizing procedures are different for the two configurations with some assumptions common to both. We assume that the power unit supplies the total power necessary for grade climbing in both the configurations. The battery usually supplies the difference between the power required to accelerate from zero to 60 mph and that for grade climbing. The battery power would be higher if the HEV is required to have some all-electric travel capability unless much lower acceleration capability was acceptable for the all-electric vehicle operations.

When HEV's internal combustion engine (ICE) power unit is sized to meet the minimum grade-climbing power and the battery pack is sized to meet the difference between acceleration and grade-climbing power values, the battery-supplied power is usually greater than 25% of the total HEV power. Such HEVs are termed *full* HEVs. The ICE represents a mature and affordable technology while the electric drive, consisting of motor, inverter/controller, and battery pack, represents an evolving technology. Consequently, it would be economical to reduce the size of the electric drive in some cases. By specifying a higher grade-climbing requirement and keeping the Z60 time unchanged, a user may increase the power rating of the ICE power unit. Since traction motor and battery provide the difference between acceleration and grade-climbing power requirements, their sizes are reduced with increase in the gradeability specification. Consequently, the battery power share of total power drops. Such HEVs are termed *mild* HEVs.

## Series HEV

Figure 3 shows a schematic diagram of the series HEV drivetrain. The power unit is connected to the generator. The generator supplies power to either the motor or the battery pack. The battery pack supplies power to the motor and also receives some recharge electricity fed back from the motor (acting as a generator) during regenerative braking. The motor is connected to the transmission (or reduction gears) to drive the wheels. The gears also transmit power back to the motor during regenerative braking.

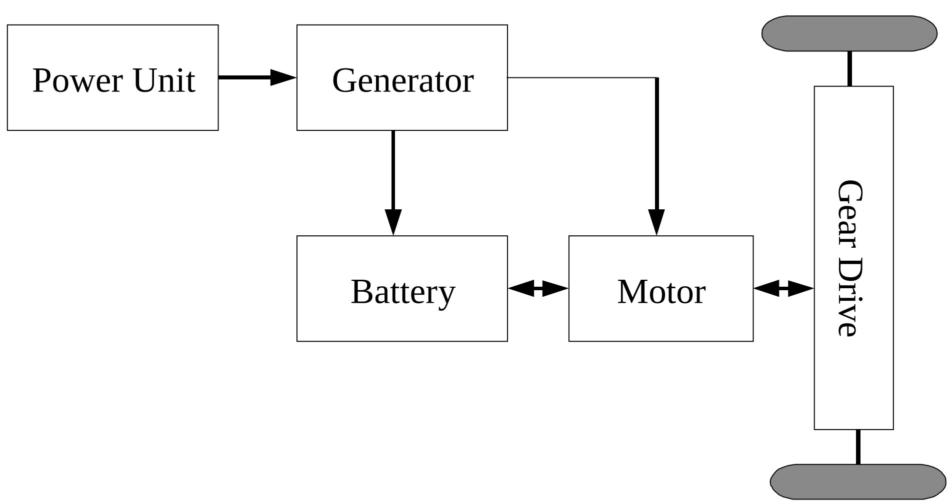



**Figure 3 Series HEV Drivetrain Components and Their Connections**

Let $\eta_{gen}$, $\eta_{mot}$, and $\eta_{tran}$ be the average power efficiency of the generator, motor, and transmission, respectively. These efficiencies are for the component assemblies including supporting units. The formulas for computing acceleration power requirement $P_a$ and grade-climbing power requirement $P_g$ are specified in equations 9 and 13, respectively. The component power ratings for a series HEV that is not required to have any all-electric acceleration capability can be computed as follows:

$$P_{pu} = P_g / \eta_{tran} \eta_{mot} \eta_{gen} \tag{23}$$

$$P_{gen} = P_g / \eta_{tran} \eta_{mot} \tag{24}$$

$$P_{mot} = P_a / \eta_{tran} \tag{25}$$

$$P_{bat} = \left(P_a - P_g\right) / \eta_{tran} \eta_{mot} \tag{26}$$

The acceleration power requirement is assumed to be larger than the grade-climbing power requirement in the above equations. Alternatively, the PU power can be computed on the basis of the smaller of $P_a$ and $P_g$, with motor power based on the larger of the two values, and battery power on the absolute value of the difference. The grade-climbing power requirement will exceed the acceleration power requirement when the grade to be negotiated is high and the time allowed to accelerate from zero to 60 mph is also high. In such a case, the battery would be used only at low speeds and during grade climbing. The battery would also serve its usual function of a sink to absorb excess energy during the periods of low power demand and braking. The motor power should always be based on the larger of the two power requirements to satisfy the highest power demand.

A series HEV that is required to have an all-electric acceleration capability will have a larger battery pack. This battery pack size is determined by the time required to accelerate from a stop to the maximum speed $v_m$ on battery power alone. Let $P_e$ be the all-electric acceleration power requirement:

$$P_e = a' M_v + b' \tag{27}$$

Where $a'$ and $b'$ are parameters that match the required all-electric acceleration time $t_m$ in equation 8.

The battery power is computed as follows:

$$P_{bat} = P_e / \eta_{tran} \eta_{mot} \tag{28}$$

The equations 9 and 13 for power computation require that the vehicle inertia mass $M_v$ be known. However, the vehicle inertia mass has four contributors (see equation 16): body, chassis, drivetrain, and load. The body and chassis mass depend on the type of vehicle (i.e., small or midsize car) and type of material (i.e., conventional steel, ultralight steel, or aluminum) while the drivetrain mass depends on the power requirements. The load is usually fixed, but may have different values for acceleration and grade climbing (the PNGV vehicle criteria measure acceleration with a load of 300 pounds, whereas gradeability is measured with a higher load of 1100 pounds). Thus, the power and mass computation, in part, depend on the drivetrain component mass.

## Mass for a Series HEV with No All-Electric Acceleration Capability

The total vehicle mass $M_{veh}$ is defined as:

$$M_{veh} = M_f + M_{dt}$$

where

$M_f$ = Fixed mass (i.e., sum of body and chassis mass),

$M_{dt}$ = Drivetrain mass,

Let

$P_a$ = Power requirements for acceleration,

$P_g$ = Power requirements for grade climbing,

$M_c$ = Mass of drivetrain component "c",

$P_c$ = Power rating of drivetrain component "c",

$S_c$ = Specific power of drivetrain component "c", and

$\eta_c$ = efficiency of drivetrain component "c."

Then the drivetrain mass is estimated as shown below:

$$\begin{aligned}
M_{dt} &= M_{mot} + M_{pu} + M_{gen} + M_{bat} + M_{tran} \\
&= \frac{P_{mot}}{S_{mot}} + \frac{P_{pu}}{S_{pu}} + \frac{P_{gen}}{S_{gen}} + \frac{P_{bat}}{S_{bat}} + \frac{P_{tran}}{S_{tran}} \\
&= \frac{P_a}{\eta_{tran} S_{mot}} + \frac{P_g}{\eta_{tran}\eta_{gen}\eta_{mot} S_{pu}} + \frac{P_g}{\eta_{tran}\eta_{mot} S_{gen}} + \frac{P_a - P_g}{\eta_{tran}\eta_{mot} S_{bat}} + \frac{P_a}{\eta_{tran} S_{tran}} \\
&= P_a\left(\frac{1}{\eta_{tran} S_{mot}} + \frac{1}{\eta_{tran}\eta_{mot} S_{bat}} + \frac{1}{\eta_{tran} S_{tran}}\right) + P_g\left(\frac{1}{\eta_{tran}\eta_{mot}\eta_{gen} S_{pu}} + \frac{1}{\eta_{tran}\eta_{mot} S_{gen}} - \frac{1}{\eta_{tran}\eta_{mot} S_{bat}}\right) \\
&= e_s P_a + f_s P_g \qquad (29)
\end{aligned}$$

Here

$$e_s = \left( \frac{1}{\eta_{tran} S_{mot}} + \frac{1}{\eta_{tran} \eta_{mot} S_{bat}} + \frac{1}{\eta_{tran} S_{tran}} \right) = \frac{1}{\eta_{trans}} \left( \frac{1}{S_{mot}} + \frac{1}{\eta_{mot} S_{bat}} + \frac{1}{S_{tran}} \right)$$

$$f_s = \left( \frac{1}{\eta_{tran} \eta_{mot} \eta_{gen} S_{pu}} + \frac{1}{\eta_{tran} \eta_{mot} S_{gen}} - \frac{1}{\eta_{tran} \eta_{mot} S_{bat}} \right) = \frac{1}{\eta_{trans}} \left( \frac{1}{\eta_{mot} t \eta_{gen} S_{pu}} + \frac{1}{\eta_{mot} S_{gen}} - \frac{1}{\eta_{mot} S_{bat}} \right)$$

Total vehicle mass $M_{veh} = M_f + M_{dt} = M_f + e_s P_a + f_s P_g$ .

Note that acceleration power $P_a$ and grade-climbing power $P_g$ are computed with inertia mass values that include some load. The design factor $k$ is applied to account for other losses.

$$M_{veh} = M_f + e_s k[a(M_{veh} + M_{aload}) + b] + f_s k[c(M_{veh} + M_{gload}) + d]$$

where

$M_{aload}$ = the load during acceleration and

$M_{gload}$ = the load during grade climbing.

$$M_{veh} - e_s k a M_{veh} - f_s k c M_{veh} = M_f + e_s k(aM_{aload} + b) + f_s k(cM_{gload} + d)$$

$$M_{veh} = \frac{M_f + e_s k(aM_{aload} + b) + f_s k(cM_{gload} + d)}{1 - k(e_s a + f_s c)} \qquad (30)$$

## Mass for a Series HEV with All-Electric Acceleration Capability

The above procedure applies to a series HEV that is not required to accelerate on battery power. A series HEV may be required to have some all-electric acceleration capability to reduce emissions. Such an HEV would function as an electric vehicle as long as its battery maintains a state of charge above a predetermined minimum level. The power unit would turn on when the battery charge reaches this predetermined level. The State of California appears to prefer such an HEV because it would not have any tailpipe emissions while running on battery power.

The drivetrain mass of such a series HEV is determined as follows.

Let $P_e$ = Power requirements for all-electric acceleration ($P_e <= P_a$)

Then

$$M_{dt} = M_{mot} + M_{pu} + M_{gen} + M_{bat} + M_{tran}$$

$$= \frac{P_{mot}}{S_{mot}} + \frac{P_{pu}}{S_{pu}} + \frac{P_{gen}}{S_{gen}} + \frac{P_{bat}}{S_{bat}} + \frac{P_{tran}}{S_{tran}}$$

$$= \frac{P_a}{\eta_{tran} S_{mot}} + \frac{P_g}{\eta_{tran}\eta_{gen}\eta_{mot} S_{pu}} + \frac{P_g}{\eta_{tran}\eta_{mot} S_{gen}} + \frac{P_e}{\eta_{tran}\eta_{mot} S_{bat}} + \frac{P_a}{\eta_{tran} S_{tran}}$$

$$= P_a\left(\frac{1}{\eta_{tran} S_{mot}} + \frac{1}{\eta_{tran} S_{tran}}\right) + P_g\left(\frac{1}{\eta_{tran}\eta_{mot}\eta_{gen} S_{pu}} + \frac{1}{\eta_{tran}\eta_{mot} S_{gen}}\right) + P_e\left(\frac{1}{\eta_{tran}\eta_{mot} S_{bat}}\right)$$

$$= e_s' P_a + f_s' P_g + h_s' P_e \quad (31)$$

where

$$e_s' = \frac{1}{\eta_{tran}}\left(\frac{1}{S_{mot}} + \frac{1}{S_{tran}}\right),$$

$$f_s' = \frac{1}{\eta_{tran}}\left(\frac{1}{\eta_{mot}\eta_{gen} S_{pu}} + \frac{1}{\eta_{mot} S_{gen}}\right), \text{ and}$$

$$h_s' = \frac{1}{\eta_{tran}\eta_{mot} S_{bat}}.$$

Total vehicle mass $M_{veh} = M_f + M_{dt} = M_f + e_s' P_a + f_s' P_g + h_s' P_e$.

The power requirements $P_a$ *and* $P_e$ are computed with a load of $M_{aload}$ and $P_g$ is computed with a load of $M_{gload}$. Also, the design factor $k$ is applied:

$$M_{veh} = M_f + e_s' k[a(M_{veh} + M_{aload}) + b] + f_s' k[c(M_{veh} + M_{gload}) + d] + h_s' k[a'(M_{veh} + M_{aload}) + b']$$

where $a'$ and $b'$ are the parameters that match the all-electric acceleration time requirement.

$$M_{veh} - e_s' kaM_{veh} - f_s' kcM_{veh} - h_s' ka' M_{veh} = M_f + e_s' k(aM_{aload} + b) + f_s' k(cM_{gload} + d) +$$

$$h_s' k(a' M_{aload} + b')$$

$$M_{veh} = \frac{M_f + e_s' k(aM_{aload} + b) + f_s' k(cM_{gload} + d) + h_s' k(a' M_{aload} + b')}{1 - k\left(e_s' a + f_s' c + h_s' a'\right)} \quad (32)$$

## Parallel HEV

A schematic diagram of the parallel HEV drivetrain is shown in Figure 4. In a parallel HEV, both power unit and motor supply power to the wheels. A generator is optional because the motor can be reversed during episodes of low power demand to recharge the battery. Normally, the motor is the primary source of power during low speeds and congested conditions. Since extended periods of congested driving under such a control strategy could drain the battery and the motor cannot generate any power to recharge the battery when the vehicle is stopped, parallel HEVs may be equipped with a generator. In our analysis, we assumed that all parallel HEVs would be equipped with a generator.

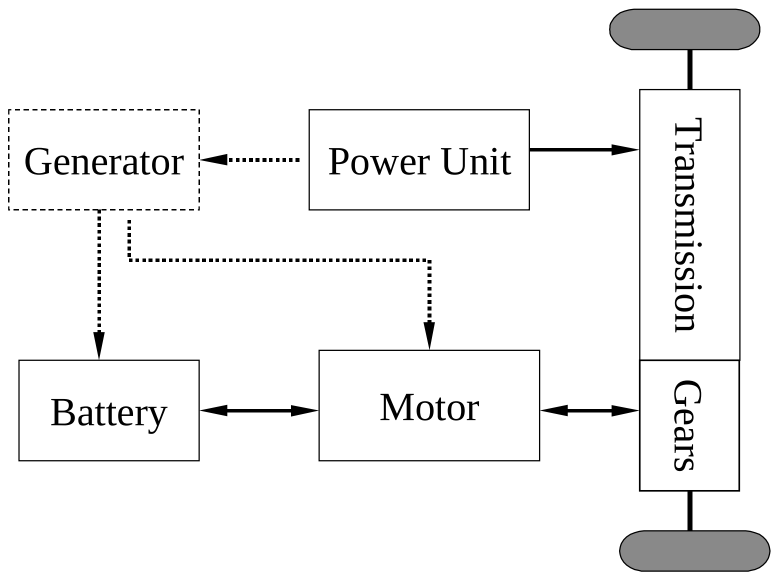



**Figure 4 Parallel HEV Drivetrain Components and Their Connections**

The power rating of the generator would depend on the vehicle control strategy. It could supply power directly to the motor or only to the battery pack. Thus, a generator's power rating could be equal to or lower than the power rating of the motor. We assumed the generator to have one-third the power rating of the power unit in our computations. Using the earlier described convention, the power ratings of parallel HEV drivetrain components are computed as follows, assuming no all-electric acceleration capability:

$$P_{pu} = P_g / \eta_{tran} \tag{33}$$

$$P_{gen} = P_g / 3\eta_{tran}\,\eta_{mot} \tag{34}$$

$$P_{mot} = (P_a - P_g) / \eta_{trant} \tag{35}$$

$$P_{bat} = (P_a - P_g)/\eta_{tran}\eta_{mot} \quad (36)$$

In the above computations, acceleration power demand is assumed to be larger than the grade-climbing power demand. This assumption is true for most driving conditions in the United States. The battery supplies the difference between acceleration and grade-climbing power demands. The motor is connected to the transmission and uses power from either the battery or the generator. The motor may draw power from both the battery and the generator under some control strategies.

A parallel HEV may be required to have some all-electric acceleration and travel capability. Such a parallel HEV would have a larger battery pack, a larger motor, and could benefit from a larger generator. However, the generator size is limited by the PU power rating, its prime mover. The power requirements for these three components are determined as follows:

All-electric acceleration power requirement $P_e = a' M_v + b'$.

where $a'$ and $b'$ satisfy the all-electric acceleration time requirement.

$$P_{bat} = P_e/\eta_{tran}\eta_{mot} \quad (37)$$

$$P_{mot} = P_e/\eta_{tran} \quad (38)$$

$$P_{gen} = P_g / 3\eta_{tran}\eta_{mot} \quad (39)$$

## Mass for a Parallel HEV with No All-Electric Acceleration Capability

The total vehicle mass $M_{veh} = M_f + M_{dt}$

Where $M_f$ is the fixed mass and $M_{dt}$ is the drivetrain mass.

$$M_{dt} = M_{mot} + M_{pu} + M_{gen} + M_{bat} + M_{tran}$$

$$= \frac{P_{mot}}{S_{mot}} + \frac{P_{pu}}{S_{pu}} + \frac{P_{gen}}{S_{gen}} + \frac{P_{bat}}{S_{bat}} + \frac{P_{tran}}{S_{tran}}$$

$$= \frac{P_a - P_g}{\eta_{tran}S_{mot}} + \frac{P_g}{\eta_{tran}S_{pu}} + \frac{P_g}{3\eta_{tran}\eta_{mot}S_{gen}} + \frac{P_a - P_g}{\eta_{tran}\eta_{mot}S_{bat}} + \frac{P_a}{\eta_{tran}S_{tran}}$$

$$= P_a\left(\frac{1}{\eta_{tran}S_{mot}} + \frac{1}{\eta_{tran}\eta_{mot}S_{bat}} + \frac{1}{\eta_{tran}S_{tran}}\right) +$$

$$P_g\left(\frac{1}{\eta_{tran}S_{pu}} - \frac{1}{\eta_{tran}S_{mot}} + \frac{1}{3\eta_{tran}\eta_{mot}S_{gen}} - \frac{1}{\eta_{tran}\eta_{mot}S_{bat}}\right)$$

$$= e_pP_a + f_pP_g \quad (40)$$

where

$$e_p = \frac{1}{\eta_{tran}}\left(\frac{1}{S_{mot}} + \frac{1}{\eta_{mot} S_{bat}} + \frac{1}{S_{tran}}\right) \text{ and}$$

$$f_p = \frac{1}{\eta_{tran}}\left(\frac{1}{S_{pu}} - \frac{1}{S_{mot}} + \frac{1}{3\eta_{mot} S_{gen}} - \frac{1}{\eta_{mot} S_{bat}}\right).$$

The vehicle mass $M_{veh}$ can be computed the same way as was done for the series HEV (see equation 30):

$$M_{veh} = \frac{M_f + e_p k(aM_{aload} + b) + f_p k(cM_{gload} + d)}{1 - k(e_p a + f_p c)} \tag{41}$$

## Mass for a Parallel HEV with All-Electric Acceleration Capability

A parallel HEV that is required to have some all-electric acceleration capability would likely have a larger battery pack, motor, and generator. The drive train mass is computed as follows:

$$M_{dt} = \frac{P_g + P_e}{\eta_{tran} S_{tran}} + \frac{P_g}{\eta_{tran} S_{pu}} + \frac{P_e}{\eta_{tran} S_{mot}} + \frac{P_g}{3\eta_{tran}\eta_{mot} S_{gen}} + \frac{P_e}{\eta_{tran}\eta_{mot} S_{bat}}$$

$$= \frac{P_g}{\eta_{tran}}\left(\frac{1}{S_{tran}} + \frac{1}{S_{pu}} + \frac{1}{3\eta_{mot} S_{gen}}\right) + \frac{P_e}{\eta_{tran}}\left(\frac{1}{S_{tran}} + \frac{1}{S_{mot}} + \frac{1}{\eta_{mot} S_{bat}}\right)$$

$$= f_p' P_g + h_p' P_e \tag{42}$$

where

$$f_p' = \frac{1}{\eta_{tran}}\left(\frac{1}{S_{tran}} + \frac{1}{S_{pu}} + \frac{1}{3\eta_{mot} S_{gen}}\right) \text{ and}$$

$$h_p' = \frac{1}{\eta_{tran}}\left(\frac{1}{S_{tran}} + \frac{1}{S_{mot}} + \frac{1}{\eta_{mot} S_{bat}}\right).$$

Notice that $h_p'$ is computed the same way as $e_p$ in equation 40.

The vehicle mass $M_{veh}$ is computed as follows:

$$M_{veh} = M_f + f_p' kP_g + h_p' kP_e$$

$$= M_f + f_p' k[c(M_{veh} + M_{gload}) + d)] + h_p' k[a'(M_{veh} + M_{aload}) + b']$$

$$= \frac{M_f + f'_p k(cM_{gload} + d) + h'_p k(a' M_{aload} + b')}{1 - k\left( f'_p c + h'_p a' \right)} \qquad (43)$$

## Application of the Procedure

The following example demonstrates the application of the above-described power and mass computing procedure to a midsize car. Data for the example were gathered from several sources and were complemented with technical judgment in some cases.

### Midsize HEV

Two midsize cars (1998 model year Chrysler Cirrus and Chevrolet Malibu) provide a baseline conventional vehicle (CV) for this example. The cars have an average mass of 1,418 kg (3,125 lb). Assuming that the future cars will use ultralight steel, we can assign a mass of 1,322 kg (2,915 lb) in 2005, an 11% reduction. We assume that more improvements will result in a 0.5% reduction in mass every 5 years after 2005. We also assume that the body and chassis mass contribute 73.5% of the total vehicle mass (Stodolsky et al. 1995a). An HEV's body and chassis are assumed to have 5% higher mass than a CV's due to additional components for power electronics and stiffeners to support the battery pack. The resulting body and chassis mass values are shown in Table 1. Three body types are listed in Table 1: (1) ultralight steel body, (2) partial aluminum body, and (3) maximum aluminum body. A partial aluminum vehicle could weigh 10% less than its ultralight steel body counterpart and a maximum aluminum vehicle could weigh 22% less than its ultralight steel body counterpart (Stodolsky et al. 1995b).

The selected baseline vehicles are 70.5 inches wide and 55.3 inches tall. These dimensions were kept unchanged in this analysis. A factor is applied to the vehicle cross section to account for ground clearance and side curvatures. This factor was 0.83 in 2005, 0.82 in 2010, 0.81 in 2015, and 0.80 in 2020. The resulting frontal area ranged from 2.09 square meters in 2005 to 2.01 square meters in 2020. We also assume that the future cars will have much lower aerodynamic drag coefficients and their tires will have very low rolling resistance. Table 1 also lists aerodynamic and rolling resistance parameters.

Some design criteria are necessary for computing power requirements. The vehicle is required to accelerate from zero to 60 mph (26.82 m/s) in some fixed time. It should also have sufficient power to climb a predetermined grade at a constant speed. Table 2 lists maximum grade and acceleration requirements. The vehicles characterized here are capable of negotiating

**Table 1 Midsize Vehicle Characteristics**

| Characteristics | 2005 | 2010 | 2015 | 2020 |
|---|---|---|---|---|
| **Body & Chassis Mass in kg (lb in parenthesis)** | | | | |
| Ultralight steel body | 974 (2,147) | 969 (2,136) | 964 (2,125) | 959 (2,114) |
| Partial aluminum body | 876 (1,931) | 872 (1,922) | 868 (1,914) | 863 (1,903) |
| Maximum aluminum body | 759 (1,673) | 756 (1,667) | 752 (1,658) | 748 (1,649) |
| **Aerodynamic and Rolling** | | | | |
| Frontal area ($m^2$) | 2.09 | 2.06 | 2.04 | 2.01 |
| Coefficient of drag (Cd) | 0.27 | 0.26 | 0.25 | 0.24 |
| Coefficient of rolling resistance (Cr) | 0.0080 | 0.0075 | 0.0070 | 0.0065 |

**Table 2 Other Design Parameters**

| Item | 2005 | 2010 | 2015 | 2020 |
|---|---|---|---|---|
| Maximum grade at 55 mph (%) | 6.5 | 6.5 | 6.5 | 6.5 |
| Time to accelerate from zero to 60 mph (s) | 12 | 12 | 12 | 12 |
| Time to accelerate from zero to 60 mph all-electrically (s) (where applicable) | 16 | 16 | 16 | 16 |
| Loading during acceleration (kg) | 136 | 136 | 136 | 136 |
| Loading during grade climbing (kg) | 499 | 499 | 499 | 499 |

the maximum grade on PU power only. They do not have enough electrical power to negotiate these grades. We characterize two vehicles each for parallel and series hybrids. One of these two vehicles does not have any all-electric acceleration capability while the other has such a capability. The vehicles with all-electric acceleration capability would have larger battery packs that would be charged from the electricity grid. They are often referred to as grid-connected HEVs. The all-electric acceleration time is specified the same for both series and parallel grid-connected HEVs in our example. The table also shows vehicle loading during acceleration and grade climbing. The acceleration load of 136 kg is adapted from USEPA's standard procedure. The grade-climbing load of 499 kg represents 6 passengers and 91 kg of luggage and is adapted from the vehicle specifications compiled by the Partnership for a New Generation of Vehicles (PNGV).

## Battery

This example uses a modified version of the ANL's Delphi Study data for the nickel metal hydride battery (Vyas et al. 1997). Delphi respondents appear to have specified battery technologies that were prevalent in the early 1990s. These data should now reflect the availability of high specific-power batteries for HEV use (Table 3). This update was done by

**Table 3 Nickel Metal Hydride Battery Characteristics for CV-like, Grid-Independent HEV**

| Characteristic | 2005 | 2010 | 2015 | 2020 |
|---|---|---|---|---|
| Specific power at 20% SOC (W/kg) | 500 | 520 | 546 | 573 |
| Specific energy (Wh/kg) | 43 | 46 | 48 | 50 |

applying factors to the Delphi Study data. The factors for specific power and specific energy were computed by using the battery data for Toyota Prius and Toyota RAV-4.[59]

An alternative set of battery characteristics that has lower specific power and higher specific energy was developed for the grid connected HEV. Such batteries would have characteristics that fall somewhere in the middle of the characteristics of Toyota Prius and RAV-4 batteries. Factors were developed to arrive at a set of battery characteristics that would provide a range of 20 miles in 2005. The characteristics in Table 4 incorporate these factors.

### Component-Specific Power and Efficiencies

The power computation procedure requires specific power and efficiency information for each drivetrain component. Table 5 lists the values used in this analysis. We analyzed data on Unique Mobility motor SR218H and inverter CA40-300L. The motor has a peak specific power of 1,110 W/kg and the two units have a combined specific power of 875 W/kg. We assumed a 10% increase in the specific power by 2005.

## Power and Mass Computations

In this analysis, we assumed that the hybrid cars would have ultralight steel bodies. Values for such fixed parameters as gravity and air density are taken from standard physical tables. The value for gravity is 9.8 $m/s^2$ and air density is 1.23 $kg/m^3$. Also, we apply a design factor, $k$, in computing power to account for other mechanical losses and contingencies. The value of $k$ is 1.1 in these examples.

**Table 4 Nickel Metal Hydride Battery Characteristics for EV-like, Grid-Connected HEV**

| Characteristic | 2005 | 2010 | 2015 | 2020 |
|---|---|---|---|---|
| Specific power at 20% SOC (W/kg) | 335 | 350 | 370 | 385 |
| Specific energy (Wh/kg) | 49 | 52 | 54 | 56 |

[59] This calculation was completed prior to the U.S. introduction of the Prius; the U.S. version is equipped with an improved battery that attains a higher specific power than used here.

**Table 5 Specific Power and Efficiency Values for Drivetrain Components**

| Component | Type | 2005 | 2010 | 2015 | 2020 |
|---|---|---|---|---|---|
| **Specific Power (W/kg)** | | | | | |
| Motor & generator | Permanent magnet | 1,225 | 1,300 | 1,350 | 1,400 |
| Power unit | Gasoline | 325 | 330 | 335 | 340 |
| Motor with inverter | | 960 | 985 | 1,010 | 1,035 |
| Transmission | For parallel HEV | 1,300 | 1,320 | 1,340 | 1,360 |
| | For series HEV | 1,625 | 1,650 | 1,675 | 1,700 |
| **Efficiency (%)** | | | | | |
| Motor & inverter | Permanent magnet | 90 | 92 | 92 | 93 |
| Generator | Permanent magnet | 95 | 95 | 95 | 96 |
| Transmission-during acceleration | | 90 | 92 | 92 | 92 |

## Parallel HEV with No (or Minimal) All-Electric Acceleration

First we apply the procedure to the year 2005 parallel HEV that is not required to have any all-electric acceleration capability. The HEV will have the high specific-power battery with the characteristics shown in Table 3. The vehicle will accelerate from zero to 60 mph in 12 seconds. The value of exponent $x$ (in equation 3) was set at 0.56.

The power requirement $P_a$ for acceleration from zero to 60 mph (26.82 m/s) = $k(aM_v + b)$.

$$a = \frac{v_m^2}{0.1}\left[\left(\frac{t_m + 0.1}{t_m}\right)^x - 1\right] + C_r g v_m = \frac{26.82^2}{0.1}\left[\left(\frac{12 + 0.1}{12}\right)^{0.56} - 1\right] + 0.008 \times 9.8 \times 26.82$$

= 33.5 + 2.1 = 35.6 W/kg

$$b = \frac{1}{2}\rho A C_d v_m^3 = \frac{1}{2} \times 1.23 \times 2.09 \times 0.27 \times 26.82^3 = 6695.2 \text{ W}$$

The power requirement $P_g$ for grade climbing at a constant speed of 55 mph (24.59 m/s) = $k(cM_v + d)$.

$$c = g v_g(\sin\theta + C_r Cos\theta) = 9.8 \times 24.59\left(\frac{0.065}{\sqrt{1 + 0.065^2}} + 0.008 \times \frac{1}{\sqrt{1 + 0.065^2}}\right) = 17.6 \text{ W/kg}$$

$$d = \frac{1}{2}\rho A C_d v_g{}^3 = 0.5 \times 1.23 \times 2.09 \times 0.27 \times 24.59^3 = 5160.1 \text{ W}$$

$$M_{veh} = \frac{M_f + e_p k(aM_{aload} + b) + f_p k(cM_{gload} + d)}{1 - k(e_p a + f_p c)}$$

$$e_p = \frac{1}{\eta_{tran}}\left(\frac{1}{S_{mot}} + \frac{1}{\eta_{mot}S_{bat}} + \frac{1}{S_{tran}}\right) = \frac{1}{0.9}\left(\frac{1}{960} + \frac{1}{0.9\times 500} + \frac{1}{1300}\right) = 4.481\times 10^{-3}$$

$$f_p = \frac{1}{\eta_{tran}}\left(\frac{1}{S_{pu}} - \frac{1}{S_{mot}} + \frac{1}{3\eta_{mot}S_{gen}} - \frac{1}{\eta_{mot}S_{bat}}\right) = \frac{1}{0.9}\left(\frac{1}{325} - \frac{1}{960} + \frac{1}{3\times 0.9\times 1225} - \frac{1}{0.9\times 500}\right) = 0.128\times 10^{-3}$$

$$M_{veh} = \frac{974 + 4.481\times 10^{-3}\times 1.1\times(35.6\times 136 + 6695.2) + 0.128\times 10^{-3}\times 1.1\times(17.6\times 499 + 5160.1)}{1 - 1.1\times\left(4.481\times 10^{-3}\times 35.6 + 0.128\times 10^{-3}\times 17.6\right)} = 1{,}257\,\text{kg}$$

$$P_a = k(aM_v + b) = 1.1\times[35.6\times(1257 + 136) + 6695.2] = 61{,}909\,W = 61.9\text{ kW}$$

$$P_g = k(cM_v + d) = 1.1\times[17.6\times(1257 + 499) + 5160.1] = 39{,}575\,W = 39.6\text{ kW}$$

$$P_{pu} = P_g/\eta_{tran} = 39.6/0.9 = 44\text{ kW}$$

$$P_{gen} = P_g / 3\eta_{tran}\eta_{mot} = 39.6/(3\times 0.9\times 0.9) = 16.3\text{ kW}$$

$$P_{mot} = (P_a - P_g)/\eta_{tran} = (61.9 - 39.6)/0.9 = 24.8\text{ kW}$$

$$P_{bat} = (P_a - P_g)/\eta_{tran}\eta_{mot} = (61.9 - 39.6)/(0.9\times 0.9) = 27.6\text{ kW}$$

$$M_{pu} = P_{pu}/S_{pu} = 44000/325 = 135.3\text{ kg}$$

$$M_{mot} = P_{mot}/S_{mot} = 24800/960 = 25.8\text{ kg}$$

$$M_{gen} = P_{gen}/S_{gen} = 16300/1225 = 13.3\text{ kg}$$

$$M_{bat} = P_{bat}/S_{bat} = 27600/500 = 55.2\text{ kg}$$

$$M_{tran} = P_a/\eta_{tran}S_{tran} = 61900/(0.9\times 1300) = 52.9\text{ kg}$$

**Parallel HEV with All-Electric Acceleration Capability**

In this example, the parallel HEV is expected to accelerate, all-electrically, from zero to 60 mph in 16 seconds. The battery power is assumed to be available immediately and no gearshifts are necessary. The power unit is sized to provide the grade climbing power. The value of exponent *x* in equation 3 is 0.49 for all-electric acceleration. The combined power unit and battery power would be much higher than what is needed for accelerating the vehicle from zero to 60 mph in 12 seconds. The vehicle is assumed to be equipped with a battery pack that has the characteristics listed in Table 4. The battery pack has lower specific power and higher specific energy compared to the battery pack used for the parallel HEV that has no all-electric acceleration capability.

Power for accelerating the vehicle, all-electrically, from zero to 60 mph (26.82 m/s) is $Pe = k(a'\,Mv + b')$.

$$a' = \frac{v_m^2}{0.1}\left[\left(\frac{16+0.1}{16}\right)^x - 1\right] + C_r g v_m = \frac{26.82^2}{0.1}\left[\left(\frac{16.1}{16}\right)^{0.49} - 1\right] + 0.008 \times 9.8 \times 26.82 = 22 + 2.1 = 24.1\ \text{W/kg}$$

$$b' = b = 6695.2\ W$$

The values of *c* and *d* remain unchanged.

$$M_{veh} = \frac{M_f + f_p' k(cM_{gload} + d) + h_p' k(a' M_{aload} + b')}{1 - k(f_p' c + h_p' a')}$$

$$f_p' = \frac{1}{\eta_{tran}}\left(\frac{1}{S_{tran}} + \frac{1}{S_{pu}} + \frac{1}{3\eta_{mot} S_{gen}}\right) = \frac{1}{0.9}\left(\frac{1}{1300} + \frac{1}{325} + \frac{1}{3 \times 0.9 \times 1225}\right) = 4.609 \times 10^{-3}$$

$$h_p' = \frac{1}{\eta_{tran}}\left(\frac{1}{S_{tran}} + \frac{1}{S_{mot}} + \frac{1}{\eta_{mot} S_{bat}}\right)$$

$$= \frac{1}{0.9}\left(\frac{1}{1300} + \frac{1}{960} + \frac{1}{0.9 \times 335}\right) = 5.697 \times 10^{-3}$$

$$Mveh = \frac{974 + 4.609 \times 10^{-3} \times 1.1 \times (17.6 \times 499 + 5160.1) + 5.697 \times 10^{-3} \times 1.1 \times (24.1 \times 136 + 6695.2)}{1 - 1.1 \times (4.609 \times 10^{-3} \times 17.6 + 5.697 \times 10^{-3} \times 24.1)} = 1{,}457\ \text{kg}$$

$$P_e = k[a'(M_{veh} + M_{aload}) + b'] = 1.1[24.1(1457 + 136) + 6695.2] = 49{,}582\ \text{W} = 49.6\ \text{kW}$$

$$P_g = k[c(M_{veh} + M_{gload}) + d] = 1.1[17.6(1457 + 499) + 5160.1] = 43{,}441\ \text{W} = 43.4\ \text{kW}$$

$$P_{pu} = P_g / \eta_{tran} = 43.4/0.9 = 48.3\ \text{kW}$$

$$P_{mot} = P_e / \eta_{tran} = 49.6/0.9 = 55.1\ \text{kW}$$

$$P_{gen} = P_g / 3\eta_{tran}\eta_{mot} = 43.4/(3 \times 0.9 \times 0.9) = 17.9\ \text{kW}$$

$$P_{bat} = P_e / \eta_{tran}\eta_{mot} = 49.6/0.9 \times 0.9 = 61.2\ \text{kW}$$

$$M_{pu} = P_{pu} / S_{pu} = 48300/325 = 148.5\ \text{kg}$$

$$M_{mot} = P_{mot} / S_{mot} = 55100/960 = 57.4\ \text{kg}$$

$$M_{gen} = P_{gen} / S_{gen} = 17900/1225 = 14.6\ \text{kg}$$

$$M_{bat} = P_{bat} / S_{bat} = 61200/335 = 182.7\ \text{kg}$$

$$M_{tran} = \frac{P_{pu} + P_{mot}}{S_{tran}} = \frac{103400}{1300} = 79.5\,\text{kg}$$

Because this HEV has a large battery pack and a power unit that is capable of negotiating a 6.5% grade at a constant speed of 55 mph, its performance on combined PU and battery power would be very good. The acceleration time can be computed by solving the equation for time ($t_m$). The power $P_a$ is replaced by the sum of grade climbing power $P_g$ and all-electric acceleration power $P_e$.

$$P_e + P_g = k\left(\frac{v_m^2 M_v}{0.1}\left[\left(\frac{t_m + 0.1}{t_m}\right)^x - 1\right] + C_r g v_m M_v + \frac{1}{2}\rho A C_d v_m^3\right)$$

$$t_m = 0.1 \div \left(\left\{\left[\frac{\left(P_g + P_e\right)/k - 0.5\rho A C_d v_m^3 - C_r g v_m M_v}{v_m^2 M_v}\right]0.1 + 1\right\}^{1/x} - 1\right)$$

Because the Z60 time on combined PU and battery power is expected to be close to 8 seconds, we assign a value of 0.6 to the exponent *x*.

$$t_m = 0.1 \div \left(\left\{\left[\frac{93000/1.1 - 0.5\times 1.23\times 2.09\times 0.27\times 26.82^3 - 0.008\times 9.8\times 26.82\times(1457+136)}{26.82^2\times(1457+136)}\right]\times 0.1 + 1\right\}^{1/0.6} - 1\right)$$

= 9.2 seconds

### Series HEV with No All-Electric Acceleration Capability

The year 2005 series HEV would be equipped with the high specific power battery listed in Table 3. The acceleration power requirement $P_a = k(aM_v + b)$:

$$a = \frac{v_m^2}{0.1}\left[\left(\frac{12.1}{12}\right)^{0.56} - 1\right] + C_r g v_m = \frac{26.82^2}{0.1}(0.004658) + 0.008\times 9.8\times 26.82 = 33.5 + 2.1 = 35.6\,\text{W/kg}$$

The value of *b, c, and d* remain unchanged at 6695.2, 17.6, and 5160.1, respectively.

$$M_{veh} = \frac{M_f + e_s k\left(aM_{aload} + b\right) + f_s k\left(cM_{gload} + d\right)}{1 - k\left(e_s a + f_s c\right)}$$

$$e_s = \frac{1}{\eta_{trans}}\left(\frac{1}{S_{mot}} + \frac{1}{\eta_{mot} S_{bat}} + \frac{1}{S_{tran}}\right) = \frac{1}{0.94}\left(\frac{1}{960} + \frac{1}{0.9\times 500} + \frac{1}{1625}\right) = 4.13\times 10^{-3}$$

$$f_s = \frac{1}{\eta_{trans}}\left(\frac{1}{\eta_{mot}\eta_{gen}S_{pu}} + \frac{1}{\eta_{mot}S_{gen}} - \frac{1}{\eta_{mot}S_{bat}}\right) = \frac{1}{0.94}\left(\frac{1}{0.9\times 0.95\times 325} + \frac{1}{0.9\times 1225} - \frac{1}{0.9\times 500}\right) = 2.43\times 10^{-3}$$

$$Mveh = \frac{974 + 4.13\times 10^{-3}\times 1.1(35.6\times 136 + 6695.2) + 2.43\times 10^{-3}\times 1.1(17.6\times 499 + 5160.1)}{1 - 1.1(4.13\times 10^{-3}\times 35.6 + 2.43\times 10^{-3}\times 17.6)} = 1{,}344\ \text{kg}$$

$$P_a = 1.1[35.6(1344 + 136) + 6695.2] = 65{,}331\,\text{W} = 65.3\,\text{kW}$$

$$P_g = 1.1[17.6(1344 + 499) + 5160.1] = 41{,}262W = 41.3\,\text{kW}$$

$$P_{pu} = 41.3/0.94\times 0.9\times 0.95 = 51.3\,\text{kW}$$

$$P_{gen} = 41.3/0.94\times 0.9 = 48.8\,\text{kW}$$

$$P_{mot} = Max[65.3/0.9\,4, 41.3/(0.94\times 0.675)] = 69.5\,\text{kW}$$

The above motor power shows its peak power rating based on the higher of the two power needs: (1) for acceleration and (2) for grade climbing. We used the motor's peak power rating for the acceleration power requirement, which is to be met for 12 seconds. Because the motor is required to provide constant grade climbing power for 20 minutes or more, we used the motor's constant power rating for grade climbing. A ratio of 0.675 between constant and peak specific power, derived from the runs of Advanced Vehicle Simulator (ADVISOR) for the Unique Mobility motor SR218H, is used here:

$$P_{bat} = (65.3 - 41.3)/0.94\times 0.9 = 28.5\,\text{kW}$$

$$M_{pu} = 51300/325 = 158\,\text{kg}$$

$$M_{gen} = 48800/1225 = 39.8\,\text{kg}$$

$$M_{mot} = 69500/960 = 72.4\,\text{kg}$$

$$M_{bat} = 28500/500 = 57\,\text{kg}$$

$$M_{tran} = 65300/(1625\times 0.94) = 42.8\,\text{kg}$$

### Series HEV with All-Electric Acceleration Capability

This series HEV will accelerate, all-electrically, from zero to 60 mph in 16 seconds. The battery, which has the characteristics in Table 4, is sized to provide the power for this acceleration. The motor is sized to provide constant power for grade climbing because its constant power rating is assumed to be only 67.5 of the peak power rating.

$$a' = \frac{v_m^2}{0.1}\left[\left(\frac{t_m + 0.1}{t_m}\right)^x - 1\right] + C_r g v_m = \frac{26.82^2}{0.1}\left(\frac{16.1}{16}\right)^{0.49} + 0.008 \times 9.8 \times 26.82 = 24.1\,\text{W/kg}$$

$$b' = b = 6695.2$$

The values of *a, b, c, and d* remain unchanged at 35.6, 6695.2, 17.6, and 5158.4, respectively.

$$M_{veh} = \frac{M_f + e_s^{'} k(aM_{aload} + b) + f_s^{'} k(cM_{gload} + d) + h_s^{'} k(a' M_{aload} + b')}{1 - k\left(e_s^{'} a + f_s^{'} c + h_s^{'} a'\right)}$$

$$e_s^{'} = \frac{1}{\eta_{tran}}\left(\frac{1}{S_{mot}} + \frac{1}{S_{tran}}\right) = \frac{1}{0.94}\left(\frac{1}{960} + \frac{1}{1625}\right) = 1.76 \times 10^{-3}$$

$$f_s^{'} = \frac{1}{\eta_{tran}}\left(\frac{1}{\eta_{mot}\eta_{gen}S_{pu}} + \frac{1}{\eta_{mot}S_{gen}}\right) = \frac{1}{0.94}\left(\frac{1}{0.9 \times 0.95 \times 325} + \frac{1}{0.9 \times 1225}\right) = 4.79 \times 10^{-3}$$

$$h_s^{'} = \frac{1}{\eta_{tran}\eta_{mot}S_{bat}} = \frac{1}{0.94 \times 0.9 \times 335} = 3.53 \times 10^{-3}$$

$$M_{veh} = \frac{974 + 1.76 \times 10^{-3} \times 1.1(35.6 \times 136 + 6695.2) + 4.79 \times 10^{-3} \times 1.1(17.6 \times 499 + 5158.4) + 3.53 \times 10^{-3} x 1.1(24.1 \times 136 + 6695.2)}{1 - 1.1(1.76 \times 10^{-3} \times 35.6 + 4.79 \times 10^{-3} \times 17.6 + 3.53 \times 10^{-3} \times 24.1)}$$

=1,488 kg

$$P_a = 1.1[35.6(1488 + 136) + 6695.2] = 70982\text{ W} = 71\,\text{kW}$$

$$P_g = 1.1[17.6(1488 + 499) + 5158.4] = 44{,}041\,\text{W} = 44\,\text{kW}$$

$$P_e = 1.1[24.1(1488 + 136) + 6695.2] = 50{,}414\,\text{W} = 50.4\,\text{kW}$$

$$P_{pu} = P_g / \eta_{tran}\eta_{gen}\eta_{mot} = 44/(0.94 \times 0.95 \times 0.9) = 54.8\,\text{kW}$$

$$P_{mot} = Max(P_a/\eta_{tran}, P_g/C\eta_{tran}) = 71/0.94 = 75.5\,\text{kW}$$

(C = constant to peak power ratio = 0.675)

$$P_{gen} = P_g/\eta_{tran}\eta_{mot} = 44/(0.94 \times 0.9) = 52.1\text{kW}$$

$$P_{bat} = P_e/\eta_{tran}\eta_{mot} = 50.4/(0.94 \times 0.9) = 59.6\,\text{kW}$$

$$M_{pu} = 54800/325 = 168.6\,\text{kg}$$

$$M_{mot} = 75500/960 = 78.7\,\text{kg}$$

$$M_{gen} = 52100/1225 = 42.5\,\text{kg}$$

$$M_{bat} = 59600/335 = 177.9\ \text{kg}$$

$$M_{tran} = 71000/(0.94 \times 1625) = 46.5\,\text{kg}$$

This grid-connected HEV has a combined power of 111 kW from its generator and battery that can be delivered to its wheels. However, its motor has a peak power of only 75.5 kW. Its Z60 time on combined power unit and battery power is limited by the size of its motor. Because the motor is sized to meet a 12-second Z60 time, the HEV cannot accelerate any faster.

## References


AISI, 1998, *UltraLight Steel Auto Body Final Report*, American Iron and Steel Institute, Washington, D.C.

Duleep, K.G., 1998, *Briefing on Technology and Cost of Toyota Prius*, prepared for the Office of Transportation Technology, U.S. Department of Energy, Washington, D.C., April.

OTA, 1995, *Advanced Automotive Technology: Visions of a Super-Efficient Family Car*, OTA Report OTA-ETT-638, Office of Technology Assessment, U.S. Congress, Washington, D.C.

Stodolsky, F., A. Vyas, and R. Cuenca, 1995a, *Lightweight Materials in the Light-Duty Passenger Vehicle Market: Their Market Penetration Potential and Impacts*, presented at the Second World Car Conference, University of California at Riverside, Riverside, Calif., March.

Stodolsky, F., A. Vyas, R. Cuenca, and L. Gaines, 1995b, *Life-Cycle Energy Savings Potential from Aluminum-Intensive Vehicles,* in *Proceedings of the 1995 Total Life Cycle Conference (P-293)*, SAE International, Warrendale, Pa., Oct.

Vyas, A.D., H.K. Ng, D.J. Santini, and J.L. Anderson, 1997, *Electric and Hybrid Electric Vehicles: A Technology Assessment Based on a Two-Stage Delphi Study,* Argonne National Laboratory Report ANL/ESD-36, Argonne, Ill., Dec.

Toyota, 1997, *Toyota Hybrid System*, Toyota Press Information ’97, Tokyo, Japan.