EPRI

Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options for Compact Sedan and Sport Utility Vehicles

Technical Report

Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options for Compact Sedan and Sport Utility Vehicles

1006892

Final Report, July 2002

EPRI Project Manager
M. Duvall

EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

THIS DOCUMENT WAS PREPARED BY THE ORGANIZATION(S) NAMED BELOW AS AN ACCOUNT OF WORK SPONSORED OR COSPONSORED BY THE ELECTRIC POWER RESEARCH INSTITUTE, INC. (EPRI). NEITHER EPRI, ANY MEMBER OF EPRI, ANY COSPONSOR, THE ORGANIZATION(S) BELOW, NOR ANY PERSON ACTING ON BEHALF OF ANY OF THEM:

(A) MAKES ANY WARRANTY OR REPRESENTATION WHATSOEVER, EXPRESS OR IMPLIED, (I) WITH RESPECT TO THE USE OF ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT, INCLUDING MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE, OR (II) THAT SUCH USE DOES NOT INFRINGE ON OR INTERFERE WITH PRIVATELY OWNED RIGHTS, INCLUDING ANY PARTY'S INTELLECTUAL PROPERTY, OR (III) THAT THIS DOCUMENT IS SUITABLE TO ANY PARTICULAR USER'S CIRCUMSTANCE; OR

(B) ASSUMES RESPONSIBILITY FOR ANY DAMAGES OR OTHER LIABILITY WHATSOEVER (INCLUDING ANY CONSEQUENTIAL DAMAGES, EVEN IF EPRI OR ANY EPRI REPRESENTATIVE HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES) RESULTING FROM YOUR SELECTION OR USE OF THIS DOCUMENT OR ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT.

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

Arthur D. Little
Southern California Edison
Sacramento Municipal Utility District
Electric Power Research Institute
University of California Davis
Standard & Poor
Argonne National Laboratory
National Renewable Energy Laboratory
South Coast Air Quality Management District
California Air Resources Board

ORDERING INFORMATION

Requests for copies of this report should be directed to EPRI Orders and Conferences, 1355 Willow Way, Suite 278, Concord, CA 94520, (800) 313-3774, press 2 or internally x5379, (925) 609-9169, (925) 609-1310 (fax).

Electric Power Research Institute and EPRI are registered service marks of the Electric Power Research Institute, Inc. EPRI. ELECTRIFY THE WORLD is a service mark of the Electric Power Research Institute, Inc.

Copyright © 2002 Electric Power Research Institute, Inc. All rights reserved.

CITATIONS

This report was prepared by

Arthur D. Little

Principal Investigator
L. Browning

Southern California Edison

Principal Investigator
D. Taylor

Electric Power Research Institute

Principal Investigators
M. Duvall and R. Graham

University of California Davis

Principal Investigators
A. Frank and R. Schurhoff

South Coast Air Quality Management District

Principal Investigator
L. Mirisola

Argonne National Laboratory

Principal Investigators
D. Santini and A. Vyas

National Renewable Energy Laboratory

Principal Investigator
T. Markel

Standard & Poor

Principal Investigator
A. Miller

Sacramento Municipal Utility District

Principal Investigator
W. Warf

California Air Resources Board

Principal Investigators
C. Childers and A. Bevan

This report describes research sponsored by EPRI.

The report is a corporate document that should be cited in the literature in the following manner:

Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options for Compact Sedan and Sport Utility Vehicles, EPRI, Palo Alto, CA: 2002. 1006892.

REPORT SUMMARY

This study continues the Hybrid Electric Vehicle Working Group (WG) project in which EPRI brought together representatives of the utility and automotive industries, along with those of the U.S. Department of Energy (DOE), other regulatory agencies, and university research organizations. The study, the third in a series of three studies, examines the performance, energy economy, fuel cycle emissions, costs, and consumer acceptance for compact and sports utility hybrid electric vehicles and their conventional counterparts.

Background

Several automobile companies are introducing hybrid electric vehicles (HEV), with others expected to follow soon. These early HEVs vary in many ways: vehicle platform; the size of their engines, electric motors, and batteries; and, operational control algorithms, to name a few. How these various components are sized, packaged, and controlled will substantially impact benefits the vehicle system is likely to provide in fuel savings, environmental impact, performance, and customer acceptance.

Many early HEV designs run exclusively on fossil fuels. Other HEV designs could provide a portion of the vehicle's range using grid-supplied electricity if the vehicle design accommodated more on-board energy storage. More on-board storage also would allow manufacturers to offer some benefits of electric vehicles, such as quiet operation and the convenience of home charging. HEVs with "all electric range" would be anticipated to have different impacts and benefits than the "fuel only" counterparts, but this remains to be proven. Additionally, the cost differential for achieving anticipated benefits offered by each possible option is largely unknown.

Objective

To scientifically compare several potential HEV design options with input from automakers and other stakeholders.

Approach

This study follows two previous WG studies. The first study, *Assessment of Current Knowledge of Hybrid Vehicle Characteristics and Impacts*, defined some of the ground rules for studying HEV technology. The second study, *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options,* focused on the key attributes of HEV performance, energy economy, fuel-cycle emissions, costs, consumer acceptance, and commercialization issues for mid-sized vehicles. In this third study, the project team defined various HEV configurations through use of the Department of Energy National Renewable Energy Laboratory's hybrid electric vehicle simulation model, ADVISOR, to meet specified performance goals. Once these designs were defined, the WG used ADVISOR to estimate fuel economy for HEVs and CVs (conventional vehicles). In addition, the project team studied environmental benefits using Arthur D. Little's fuel-cycle emissions model. Vehicle and operating costs were investigated using a retail price

equivalence model starting with component costs and applying mark-ups to predict the price paid by consumers for these vehicles. Operating costs were determined for both energy costs and maintenance costs. The team determined customer preference for HEVs first using focus groups and then a choice-based market model.

Results

This report indicates that HEVs, including grid-connected (plug-in) models, can probably be designed for both compact and SUV platforms meeting performance characteristics customers are familiar with. Plug-in hybrids provide significantly improved fuel economy over CVs as well as reductions in greenhouse and smog precursor emissions and petroleum use. The study indicated a market potential for all HEVs, particularly if the price differential between the HEV and CV is minimized. The customer survey also indicated that people preferred plugging in a vehicle rather than going to the gas station. However, HEVs, especially plug-in HEVs with all-electric capability, cost more than conventional vehicles due to the extra complexity with motors, chargers, and energy storage. Battery life and costs are major disadvantages that must be overcome before HEVs can be produced in large quantities; for example, potential battery replacements can significantly increase the vehicle's life-cycle cost.

EPRI Perspective

This reports summarizes results from the first-ever public domain multi-variant study comparing benefits and impacts of CVs and HEVs (gasoline-only and dual-fuel). It provides evidence that grid-connected hybrid electric vehicles are technologically feasible and can offer significant benefits. The study was produced under EPRI's direction, but with considerable input on approach, methodology, and results by the participants of the WG. Represented organizations, in particular the individual participants, are to be commended for their interest, enthusiasm, and input in making this document possible. WG participants include the Air Resources Board (ARB), the Department of Energy and two of its national labs—National Renewable Energy Laboratory (NREL) and Argonne National Laboratory (ANL)—General Motors Corporation, Ford Motor Company, South Coast Air Quality Management District (SCAQMD), and University of California Davis Hybrid Vehicle Center as well as EPRI participants Southern California Edison, New York Power Authority, and Southern Company.

Keywords

Hybrid electric vehicles
Grid-connected HEVs
ADVISOR
Customer preference

ABSTRACT

This study examines which types of hybrid electric vehicles (HEVs) offer the best combination of environmental and efficiency benefits while meeting the driving needs and economic constraints of compact car and SUV owners. Since 1999, the Hybrid Electric Vehicle Working Group (WG), a consortium of key environmental regulatory agencies, several electric utilities, the U.S. Department of Energy and its national laboratories, major automobile manufacturers, a university research center, and EPRI, have been collaborating to systematically compare various HEV designs with each other and with comparable conventional vehicles (CVs). This study included vehicle modeling, cost modeling, consumer acceptance modeling, and an examination of commercialization issues. The study found that gasoline-fueled HEVs, including those with all-electric range (AER) could be designed to be comparable to and operate like currently available conventional vehicles. These vehicles offer improved efficiency, reduced emissions (both criteria pollutants and greenhouse gas emissions), and reduced petroleum dependency. Several hurtles still exist, however. HEVs tend to cost more than conventional vehicles, particularly with increasing AER. Battery costs and lifetimes are still uncertain, although much progress has been made on this front. Consumer preference studies show a definite market potential for all HEVs and that potential is large if the cost differential between CVs and HEVs could be minimized. Even at higher costs, the Customer Preference Survey indicates that there is still significant market potential for HEVs. Current interest by automobile manufacturers in producing compact and SUV HEVs indicate the technology is viable and that with the possible exception of the batteries, plug-in HEVs require only evolutionary engineering advances over current compact HEVs. The future market potential of HEVs, particularly plug-in HEVs, will depend on reducing total system cost and maximizing vehicle attributes desirable to the consumer.

EXECUTIVE SUMMARY

Expectations of substantially lower automobile fuel consumption and exhaust emissions have motivated interest in, and technology advancement of, hybrid electric vehicles (HEVs) in the U.S. and elsewhere for a number of years. The introductions of the Prius by Toyota and the Insight and Civic Hybrid by Honda signal that major automakers see a potential for HEVs as a competitive new automotive product. These developments raise the question of which type (or types) of HEVs will offer the best combination of environmental and efficiency benefits while meeting the driving needs and economic constraints of automobile owners.

Motivated by a common need for answers, individuals from key environmental regulating agencies, DOE and its National Laboratories, major automobile manufactures, and EPRI including several of its member electric utilities, formed the Hybrid Electric Vehicle Working Group (WG) to examine this question. Since 1999, WG members have been collaborating to systematically compare different HEV types with each other as well as with comparable conventional vehicles (CVs). The comparisons addressed all major vehicle characteristics of interest to these stakeholders: performance and driveability; efficiency in the use of gasoline and (where applicable) grid electricity; emissions of air pollutants and carbon dioxide, the major greenhouse gas; vehicle first and operating costs; and the likely vehicle preferences of the prospective owners of future HEVs compared to their counterpart CVs. The WG also commissioned and discussed a preliminary examination of the issues and opportunities associated with the introduction of HEVs as a major new automotive product.

With extensive support from the WG members’ organizations, expert contractors, and several consultants, the WG carried out its analyses and comparisons through four major study tasks:

- Modeling of selected HEV configurations to closely approximate the main performance characteristics of counterpart CVs and to estimate vehicle efficiency and emissions characteristics for representative driving cycles.
- Assessment of key cost factors, including capital, energy (motor fuel and electricity), maintenance and infrastructure, for comparisons of vehicle purchase (first) and operating costs.
- Assessment of prospective owner/user acceptance of HEVs in terms of performance and other key driving characteristics, vehicle first and operating costs factors, infrastructure implications, and the anticipated special features and societal benefits of HEVs.
- A preliminary assessment of likely commercialization issues associated with the introduction of user-acceptable HEV types, and identification of currently applicable and prospective incentives available to key stakeholders (including owners) to overcome barriers to the introduction of HEVs.

This report summarizes the approaches, findings, and conclusions for compact and sport utility vehicle (SUV) conventional and hybrid vehicles; the results for mid-size vehicles have been presented in a previous report. To put the study's findings and conclusions in perspective, the following assumptions made by the WG are noted:

- A year 2010 horizon was assumed for commercial availability and cost of improved HEV component technologies, especially for those currently under active development for which significant performance gains and/or cost reductions from current levels are predicted.
- A nominal vehicle life of 100,000 miles or 10 years was assumed for cost comparisons, consistent with past studies and targets of major government-funded advanced-technology vehicle component development programs. However, the HEV life cycle cost impacts of longer vehicle life assumptions (for example, 150,000 miles and/or 15 years) were examined as well.
- Production levels of 100,000 units per year were assumed for cost comparisons.
- All costs were assumed or calculated in year 2001 dollars[1].
- The HEVs studied and their counterpart conventional vehicle had gasoline-fueled engines which met the Super Low Emission Vehicle (SULEV) emission standard in 2010.

The main findings and conclusions from the four study tasks for compact and SUV conventional and hybrid vehicles were the following:

- Engine/battery hybrid vehicles, including those without electric range capability (HEV 0), as well as plug-in hybrid electric vehicles with various all-electric ranges (AER) [i.e., 20 miles AER (HEV 20) and 60 miles AER (HEV 60)], can be designed on compact, mid-size SUV and full-size SUV platforms to have key performance parameters comparable to, and operating characteristics familiar to, customers of current conventional vehicles.
- These HEV designs offer major efficiency improvements and reductions in the consumption of petroleum-based fuels, as well as substantial reductions in the emissions of air pollution precursors (nitrogen oxides and reactive organic gases) and of greenhouse gases (carbon dioxide).
- All of these efficiency and environmental benefits increase with HEV electric range capability if that capability is fully utilized. For example, a full-size SUV HEV 0 can reduce smog precursor emissions by up to 20%[2] and petroleum consumption and CO_2 emissions by 30% in representative driving. A full-size SUV HEV 60 fully charged every night could reduce emissions by 55%, energy use by 65%, CO_2 emissions by 60%, and petroleum consumption by 85%.
- A properly designed full-size SUV HEV 60 can exceed 80 mpeg[3] in all-electric mode without resorting to expensive light-weight construction or extreme body aerodynamics. It can also

---

[1] The mid-size car study discussed in Reference 1 assumed year 2000 dollars. There was less than 1 percent change in the consumer price index for new car purchases between 2000 and 2001.

[2] Smog precursor emission reductions for the HEV 0 would be less in the Greater Metropolitan Los Angeles area because emissions associated with gasoline production are capped by local regulations. The effect of local caps is significantly less pronounced for plug-in hybrids that utilize their all-electric range.

[3] Miles per equivalent gasoline gallon

exceed 55 mpeg in normal driving if charged every night. A properly designed compact car HEV 60 can exceed 130 mpeg in all-electric mode and over 100 mpeg in normal driving if charged every night.

- All of the HEVs designed and analyzed in this study will cost more than the corresponding conventional vehicle, even in mass production. Compact HEVs can cost from $2,500 to $3,600 more for an HEV 0, $4,500 to $6,100 more for an HEV 20, and $8,100 to $10,300 more for an HEV 60 when compared to a conventional compact car. Mid-size SUV HEVs can cost from $4,000 to $5,500 more for an HEV 0, $6,400 to $8,500 more for an HEV 20, and $10,100 to $13,100 more for an HEV 60 when compared to a conventional mid-size SUV. Full-size SUV HEVs can cost from $4,500 to $6,300 more for an HEV 0, $6,000 to $8,500 more for an HEV 20, and from $11,000 to $14,500 more for an HEV 60 when compared to a conventional full-size SUV. (The cost increments listed above include the cost of a vehicle's components and assembly, fully loaded with all applicable overheads, development and warranty costs, and profit margins, but do not include special manufacturer-proprietary pricing considerations. The ranges in these increments reflect the two methods used by the WG to estimate vehicle costs. Actual uncertainties are almost certainly larger because of the uncertainties in the costs of key components that are not now available commercially in volume quantities.)

- HEVs will have lower costs of energy (gasoline plus, where applicable, electricity) and maintenance, with mileage-related operating cost savings increasing as electric range capability and its utilization increase. Although substantial, it is uncertain whether these cost savings are sufficient to offset the life cycle cost impact of higher vehicle costs. If the battery must be replaced over the life of the vehicle (likely for the HEV 20 in this study if it is used to the full extent of its electric range capability), much of the operating cost advantage is lost. Accordingly, achievement of the 10-year/100,000 vehicle mile battery life (or even longer) represents the largest cost uncertainty and most important technical target, especially for plug-in HEVs with their larger, more expensive and harder-working batteries.

- Some design issues are still being studied. These include use of a single motor, which could produce some driveability issues, placement of large battery packs in the vehicle, limited battery reserve capacity under some control strategies, selection of the best battery/engine control strategy, cabin heating, battery cooling, and battery life.

- The Customer Preference study indicates definite market potential for all HEVs. That potential is large if the cost differential between HEVs and conventional vehicles could be minimized. Most of the survey participants valued the efficiency, environmental and convenience attributes especially of the plug-in HEVs. The results for the different vehicle price assumptions (Low, Base, ANL, and High) in the study show that market potential is sensitive to price, particularly for compact car buyers. For the Base and ANL price scenarios, 19% to 23% of the respondents who drive a compact vehicle would choose an HEV 0 over a conventional vehicle, 13% to 27% would choose an HEV 20 over a conventional vehicle, and 4% to 8% would choose an HEV 60 over a conventional vehicle (when each is compared to a comparable CV)[4]. For the mid-size SUV, 33% to 38% would prefer an HEV 0 over a

---

[4] It should be noted, however, that "stated preference" studies involving choices the respondents have never made before always tend to have some bias in favor of the "new" product being studied. It is well known in the automobile industry, for example, that customers do not always value operating cost reductions that a given type of

conventional vehicle, 30% to 38% would choose an HEV 20 over a conventional vehicle, and 13% to 23% would prefer an HEV 60 over a conventional vehicle. For the full-size SUV, 39% to 45% of the respondents would prefer an HEV 0 over a conventional vehicle, 40% to 46% would prefer an HEV 20 over a conventional vehicle, and 20% to 30% would prefer an HEV 60 over a conventional vehicle. These stated preferences would be higher than those listed above if government or market incentives were used to reduce the vehicle price.

- If gasoline prices increase from the $1.65 per gallon used in the study to $3.00 per gallon, significant increases in market preference for HEVs would occur, especially in the two SUV platforms. At $3.00 per gallon, mid-size SUV HEV 0's and HEV 20's are preferred over the conventional mid-size SUV, and all three full-size SUV HEV designs are preferred over the conventional full-size SUV.
- An important finding was that the majority of the study participants preferred charging (on their own premises) a vehicle with plug-in capability to fueling the vehicle at a gasoline station; only a small minority preferred fueling at gasoline stations. However, when the costs and benefits of plugging in an HEV 20 or HEV 60 each night is explained, preference for plugging in varies with price and other key attributes. The study also showed that a large majority of the survey population had ready access to the 120V AC power that will be sufficient for overnight charging of plug-in HEV batteries.[5] Together, these findings appear to significantly reduce concerns about availability and cost of the charging infrastructure.
- It is not clear why so many people prefer HEVs over their CV counterparts. However, ten HEV benefits have a high to strong influence on the purchase decision for those who prefer HEVs. This infers more than fuel cost savings could be marketed.
- The Toyota Prius, Honda Insight, and Honda Civic Hybrid are the first commercial hybrid vehicles (all HEV 0s, although technically quite different). They are available to customers in Japan, the United States, and Europe because of the willingness of Toyota and Honda to subsidize the introduction of these promising new automotive products. With the possible exception of the batteries, plug-in HEVs require only evolutionary engineering advances over HEV 0 technology to meet technical requirements. However, there are no major automaker initiatives to develop and introduce plug-in HEVs, presumably because of battery technology readiness and vehicle cost concerns. Thus, there is as yet an unclear commercialization path to realize the substantial environmental, efficiency and energy security benefits of plug-in HEVs.

The WG concluded from the deliberation of its findings that there is a need for further study of the factors most critical to the future benefits, competitiveness and market prospects, provision of incentives, and investments in development and commercialization of HEVs. This is especially true for plug-in HEVs with their basic attractiveness to consumers and potential for superior societal benefits. These factors and the associated study tasks are currently being defined, based in good part on the insights gathered in the study reported here.

---

vehicle may offer in the initial purchase decision. It addition it is not likely that HEVs will be offered in all market segments or vehicle models in the near term. Thus customer preference might be less than stated above.

[5] To fully charge an SUV HEV 60 battery overnight, a 240V AC charger will be necessary.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1

INTRODUCTION

HEVs are seen by some researchers as a very promising near-term technology for improving fuel economy and reducing emissions, particularly for Sports Utility Vehicles (SUVs). Proponents also argue that HEVs can provide improved performance for the customer and, in contrast to other advanced-technology vehicles, require no extensive new infrastructure. With many of the advantages but without the range limitation of electric vehicles, HEVs could have broad customer appeal.

HEVs, however, come in many different configurations, and even HEV proponents disagree among themselves, which of these is "best." This question motivated the Hybrid Electric Vehicle Working Group (WG), a cooperative effort of HEV stakeholders, to study the prospective efficiencies, emissions, costs, and customer acceptance of different types of HEVs, for a systematic comparison of HEVs with each other and with a conventional vehicle (CV) of similar design and performance. This report summarizes the study approach and key findings of the WG.

The study grew out of the discussions of an informal working group that in 1999 brought together knowledgeable individuals from the utility and automotive industries, regulatory agencies and consultants, and the Department of Energy. The initial working group set itself the objectives to establish what was known about hybrid vehicle characteristics and impacts based on credible sources of information; identify gaps in existing information, and define the research needed to fully characterize the different types of HEVs and compare their prospective benefits and impacts.

The working group also decided to serve as an initial forum for discussion of the rather diverse views and interests of the stakeholder members in the HEV area. It was envisioned that this group would be able to identify possible strategies and alliances for development, commercialization, and infrastructure support of hybrid vehicle propulsion systems and vehicle options. Finally, the expectation was that the work of the group would lead to increased public and private understanding and, if appropriate, support of all aspects of hybrid electric vehicle system development.

The first output of the WG's activities was an informal report, produced with the assistance of ARCADIS (now part of Arthur D. Little), titled *Assessment of Current Knowledge of Hybrid Vehicle Characteristics and Impacts*, that summarized the results of the survey of existing studies. Although valuable in collecting data and other information on HEVs, the information proved inadequate for a systematic comparison of different types of HEVs. In particular, it was left unclear how the efficiencies and emissions of HEVs deriving part of their propulsion energy from electricity supplies compare to those of HEVs that do not plug in; whether consumers would save sufficient operating cost from plugging in to pay for additional battery cost; and whether customers would see the plug-in feature as a disadvantage or as an advantage by eliminating many or most trips to gasoline stations. Each member had different interests in wanting to learn more about the different types of HEVs.

The second output of the WG was a technical report, produced with the assistance of Arthur D. Little, titled *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options.* It presented the key attributes of HEV performance, energy economy, fuel-cycle emissions, costs, consumer acceptance, and commercialization issues for mid-sized vehicles. This study is a follow-on to the mid-size car study and focuses on compact cars and SUVs. It includes:

- Modeling of representative HEV types, to ascertain the vehicles' potential for competitive performance, and to determine their emissions and efficiency characteristics for the vehicles themselves as well as for their fuel/energy supply infrastructures over driving patterns/cycles of primary interest.
- Estimation of key HEV component and vehicle costs and life cycle costs for comparison of HEVs with each other and with a baseline conventional internal combustion engine (ICE) vehicle.
- Assessment of prospects for customer acceptance of HEVs by prospective owners and users, based upon assumptions about the vehicles' performance and other key driving characteristics, costs, and infrastructure availability.

Project teams were established to conduct the study tasks between October 2001 and June 2002.

The WG agreed to restrict its analyses to HEVs with specified component and vehicle technical and costs characteristics that some researchers believed would have reasonable prospects to be or become available in the coming decade. This allowed the study to focus on technological advances anticipated in the literature based upon the assumption that public awareness and broader acceptance of these technologies would develop in that period.

2

SUMMARY AND CONCLUSIONS

2.1 Introduction

This section summarizes the study's analysis methodology and results for the compact car and two sports utility vehicle (SUV) platforms; the mid-size vehicle platform was documented in a separate report [1]. Data supporting the charts and tables in this section can be found in Appendix A. A glossary of terms follows this section.

2.2 Vehicle Designs and Platforms

As with the mid-size vehicle, only parallel hybrid configurations were considered in this study. In a parallel HEV, the combustion engine and the electric motor-battery combination can provide power to the drive axle(s) in parallel. HEVs may or may not have plug-in capability, that is, the ability to charge the batteries from a source of electric power such as the power grid. These plug-in hybrids can be operated in all-electric mode for a given distance (referred to as all-electric range or AER), utilizing only the battery and electric motor. Four vehicle designs were examined and compared:

- A conventional vehicle (CV) with an internal-combustion engine (ICE) that served as baseline for the comparisons of vehicle attributes
- A parallel hybrid with a small battery for power assist and regenerative braking but no plug-in capability and no all-electric range (HEV 0)
- A parallel hybrid that can operate like an HEV 0 but also has plug-in capability and a battery of sufficient capacity to provide about 20 miles of all-electric range (HEV 20)
- A parallel hybrid that can operate like an HEV 0 but also has plug-in capability and a battery of sufficient capacity to provide about 60 miles of all-electric range (HEV 60)

To study the above HEV designs, three platforms were considered. These include:

- A compact vehicle based upon a 2001 Saturn SL1 with a 1.9L I-4 engine
- A mid-size SUV based upon a 2001 Ford Explorer 4WD XLT with a 4.0L V-6 engine
- A full-size SUV based upon a 2001 Chevrolet Suburban 1500LS 4WD with a 5.3L V-8 engine

2.3 Vehicle Performance

The guiding principle in establishing the key performance parameters for the hybrid vehicles was that all HEVs had to be based on a conventional vehicle body and closely approximate the main performance characteristics of the CV. However, in the iterative HEV design process that was required to achieve this objective, limited trade-offs between performance and cost were permitted where such trade-offs reduced HEV costs significantly without impairing performance characteristics (such acceleration from a stop or when passing) to which vehicle owners/operators are likely to be sensitive.

2.3.1 Design Methodology and Performance

HEV and CV component and vehicle characteristics were modeled using the ADVISOR (ADvanced VehIcle SimulatOR) computer program developed by the National Renewable Energy Laboratory (NREL) with support from Department of Energy (DOE) [2,3,4]. Each HEV was conceptually designed by the WG as part of an iterative process to meet or exceed the performance of the baseline CV in several performance categories, including various acceleration, top speed, gradeability, minimum towing capability, and minimum range targets. In addition, plug-in HEVs were asked to meet these performance targets with a battery discharged down to nearly 20% state of charge (SOC), the lowest SOC permitted in the interest of good battery cycle life. In a few cases, HEV performance parameters were relaxed somewhat if matching a specific CV parameter would have increased the cost of the HEV design greatly with only marginal useful gains for the vehicle owner/operator. Similar trade-offs were made for the mid-size car and are documented in Reference 1. Detailed design parameters and performance targets for the compact and SUV platforms can be found in Appendix Tables A-1 and A-2, respectively.

- **Sustained Top Speed**—The target for all HEVs was established at 90 mph, while typical CV compact car's and SUV's top speed were estimated to be approximately 120 mph. As shown in Table 2-1, all HEVs well exceeded the target.
- **Gradeability**—The HEV gradeability targets were 7.2% at 50 mph for 15 minutes and 7.2% at 30 mph for 30 minutes, while a typical compact and SUV CV gradeability is 7.2% at 50 mph for 30 minutes. (The HEV target is equivalent to climbing one of the longest and toughest grades in the world, the road to the top of Pike's Peak in Colorado, at 50 mph.) All HEVs exceeded this target and could also maintain freeway speeds on maximum interstate highway grades.
- **Passing Performance and Standing Acceleration**—The target time to accelerate from 50 to 70 mph was 6.9 seconds for the compact car, 5.4 seconds for the mid-size SUV, and 4.8 seconds for the full-size SUV. The 0-60 mph acceleration target was 11.7 seconds for the compact car, 9.2 seconds for the mid-size SUV, and 8.5 seconds for the full-size SUV. Table 2-2 shows CV and HEV performance in 4 acceleration categories.
- **Gasoline Range**—Compact cars were designed to travel 344 miles using gasoline in the charge sustaining mode, while the mid-size and full-size SUVs were designed to travel 347 and 435 miles, respectively, using gasoline in the charge sustaining mode. Because the HEVs have superior gasoline fuel economy when compared with the CV, the HEVs' gasoline tank capacity to meet the range requirement is less than the CV's.

- **Trailer Towing**—All vehicles met the trailer-towing requirement of the corresponding conventional vehicle. The trailer towing capacity for the compact car was 450 kg, the mid-size SUV was 2270 kg, and the full-size SUV was 3175 kg.

Table 2-1
Top Speed Results in mph

Vehicle Type	CV	HEV 0	HEV 20	HEV 60
Compact Car	124	101	113	98
Mid-Size SUV	121	100	110	95
Full-Size SUV	131	111	109	96

Table 2-2
Acceleration Results

Vehicle Type	CV	HEV 0	HEV 20	HEV 60
Compact Car				
0 to 30 mph, seconds	3.4	3.6	3.5	3.0
0 to 60 mph, seconds	10.7	10.5	10.7	8.7
40 to 60 mph, seconds	4.8	5.1	5.3	4.2
50 to 70 mph, seconds	6.9	6.2	6.8	5.1
Mid-Size SUV				
0 to 30 mph, seconds	3.4	3.9	3.7	3.5
0 to 60 mph, seconds	9.2	9.3	9.2	9.3
40 to 60 mph, seconds	4.1	3.9	4.0	4.1
50 to 70 mph, seconds	5.4	5.0	5.1	5.2
Full-Size SUV				
0 to 30 mph, seconds	3.3	3.8	3.4	3.3
0 to 60 mph, seconds	8.5	8.8	8.8	8.7
40 to 60 mph, seconds	3.7	3.6	3.8	3.9
50 to 70 mph, seconds	4.8	4.6	4.9	4.9

- **High Speed Driving (HEV 20 and HEV 60)—**At a low battery SOC, both plug-in HEVs exceed the modeling target to complete the federal test cycle for aggressive and higher speed (65-80 mph) driving (US06 cycle) twice in a row for the compact car and continuously for the SUVs. All compact HEVs can do this indefinitely at low SOC, substantially exceeding the original expectations. In fact, there is enough battery capacity for the compact HEV 60 to complete this rather stringent test cycle for 50 miles using only the battery.

Modeled power train specifications for the CV and HEV designs are summarized in Table 2-3.

Table 2-3
Power Train Specifications

Vehicle	CV	HEV 0	HEV 20	HEV 60
Compact Car				
Engine Peak Power, kW	74	53	41	32
Motor Rated Power, kW	—	23	37	61
Battery Rated Capacity, kWh	—	2.2	5.1	15.4
Vehicle Mass, kg	1,209	1,221	1,292	1,381
Mid-Size SUV				
Engine Peak Power, kW	156	115	95	72
Motor Rated Power, kW	—	51	84	89
Battery Rated Capacity, kWh	—	4.1	7.9	23.4
Vehicle Mass, kg	2,256	2,333	2,402	2,546
Full-Size SUV				
Engine Peak Power, kW	212	145	115	90
Motor Rated Power, kW	—	65	98	117
Battery Rated Capacity, kWh	—	5.2	9.3	27.7
Vehicle Mass, kg	2,757	2,765	2,824	2,982

2.3.2 Design Issues

A number of design issues were identified in the efforts to model HEV performance. While there are probably solutions to each of them, they need further analysis. Further discussion can be found in Reference 1.

- **Designs Which Only Include a Single Motor** (versus two motor designs). A single motor solution may produce unacceptable shift quality and unmanageable accessory drive and engine starting.
- **Battery Pack Placement/Location** in the hybrid vehicles are a concern especially with larger battery packs such as in the HEV 60.
- **"Turtle" Light (Limited Battery Reserve Capacity)** could be a challenge for plug-in hybrids depending on which control strategy is selected.
- **Cabin Heating.** It is assumed in this study that the engine would provide the heat for the cabin, but fuel economy would be sacrificed to perform cabin heating. Other forms of heat could be used such as Positive Thermal Coefficient (PTC) heating element at a cost.
- **Battery Cooling.** Electric losses in the battery during charging and discharging generate heat that must be removed by flow of air or liquid coolant to keep the battery temperatures under control.

- **Battery Life and Battery Replacement.** Under some driving scenarios, plug-in hybrid electric vehicles may require that the battery be replaced during the nominal lifetime of the vehicle. If the vehicle is driven over 100,000 miles or operated longer than 10 years, all hybrids might need a battery replacement. However, larger battery packs tend to accumulate more miles before replacement is needed.
- **Control Strategies.** There are many control strategies than can be used with plug-in HEVs that can optimize fuel economy, emissions, and/or battery life. These should be examined in detail to determine the best possible strategy for plug-in HEVs.

2.4 Vehicle Efficiency (Fuel Economy)

The hybridization of combustion engines with electrical energy storage devices into hybrid drive trains can reduce gasoline fuel consumption in two ways. All types of HEVs can make more efficient use of gasoline because hybridization permits not only the use of smaller engines operated more efficiently but also partial recovery of vehicle kinetic energy when the vehicle is decelerating or going down a hill. In addition, plug-in HEVs permit substitution of electricity as propulsion "fuel" for part of the gasoline.

Fuel economy can be defined in several ways. Gasoline only fuel economy applies to the CV and HEV 0 in all driving modes. It also applies for the HEV 20 and the HEV 60 whenever these plug-in hybrids are driven in the charge-sustaining mode, that is, with no net change in the energy content of the battery.

Electric-only fuel economy, expressed normally as miles per unit of electric energy is converted in this report to miles per (energy) equivalent gasoline gallon (mpeg) whenever a plug-in HEV is operating in electric-only mode; the energy equivalent calculations use~~s~~ a conversion factor of 33.44 kWh per gallon of gasoline.

While plug-in hybrid electric vehicles can be operated for a given distance in electric-only mode (determined by battery capacity), trips since the battery was last charged that are longer than the HEV's all-electric range have mixed operation, i.e. some in electric-only mode and some in charge sustaining mode. The probability of a given HEV operating all its mileage in all-electric mode is referred to here as a mileage weighted probability (MWP). The MWP gives an estimation of what portion of a plug-in HEV's daily annual mileage will be operated in all-electric mode based upon national driving statistics. The Society of Automotive Engineers (SAE) subcommittee on hybrid electric vehicles also defined an all-electric usage factor which they named an Utility Factor (UF). The UF is used by ADVISOR to determine mixed fuel economy (see Reference 1 for more details on these fuel economy definitions).

Charging frequency also plays a part in determining the portion of annual miles that a plug-in HEV will operate in all-electric mode. The more often a plug-in hybrid is charged, the more likely it is to travel a greater percentage of its annual miles in all-electric mode. The SAE subcommittee also developed a recommended practice (J1711) that assumes the vehicle is just as likely to start a trip with the battery fully charged as with the battery at a low SOC. This provides a case between charging every night and not charging at all. Other cases might include charging twice daily (at home and at work), or charging every other day. The UF weighted (charging every day) and J1711 UF weighted (just as likely to start the trip with a full charge as a low SOC) fuel economies are also shown in Figure 2-1 for the compact car, Figure 2-2 for the mid-size SUV and Figure 2-3 for the full-size SUV.

As can be seen in Figures 2-1 through 2-3, there is a wide range of fuel economies for the plug-in HEVs depending on how the vehicles are operated. If they are charged every day and driven less than their all-electric range, fuel economies exceeding 130 mpeg for the compact car, 90 mpeg for the mid-size SUV, and 75 mpeg for the full-sized SUV can be achieved. Even when they are not charged at all, plug-in HEVs still provide a 45% to 60% improvement in fuel economy over the equivalent CV. As expected, the J1711 fuel economy for mixed gasoline and electricity-fueled driving falls between these two. MWP weighted fuel economy for the HEV 20 and HEV 60 for the compact car, mid-size SUV and full-size SUV (not shown in Figures 2-1, 2-2, and 2-3) are shown in Table 2-4 when the vehicles are fully charged every night.

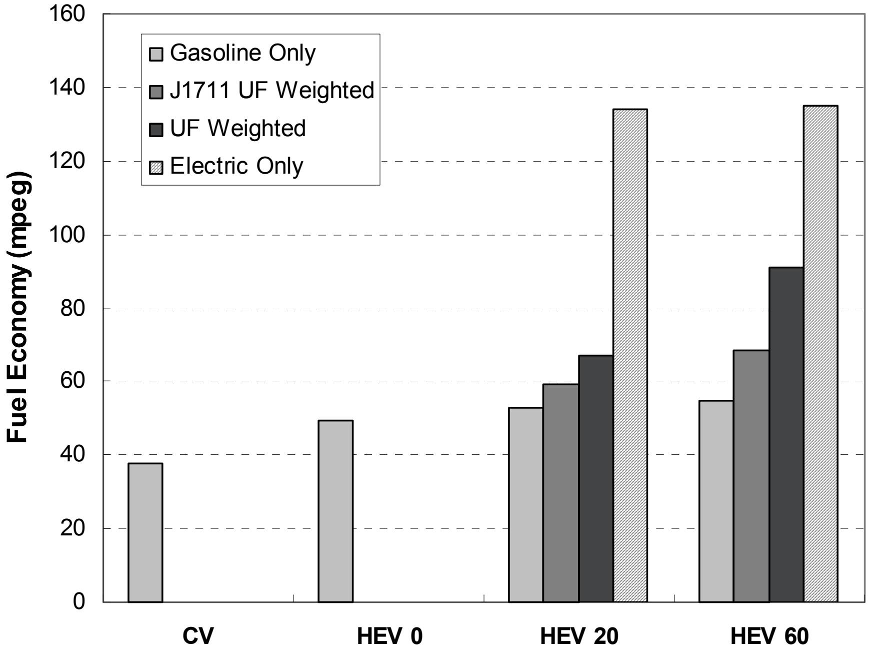

Figure 2-1
Fuel Economy Comparisons for the Compact Car

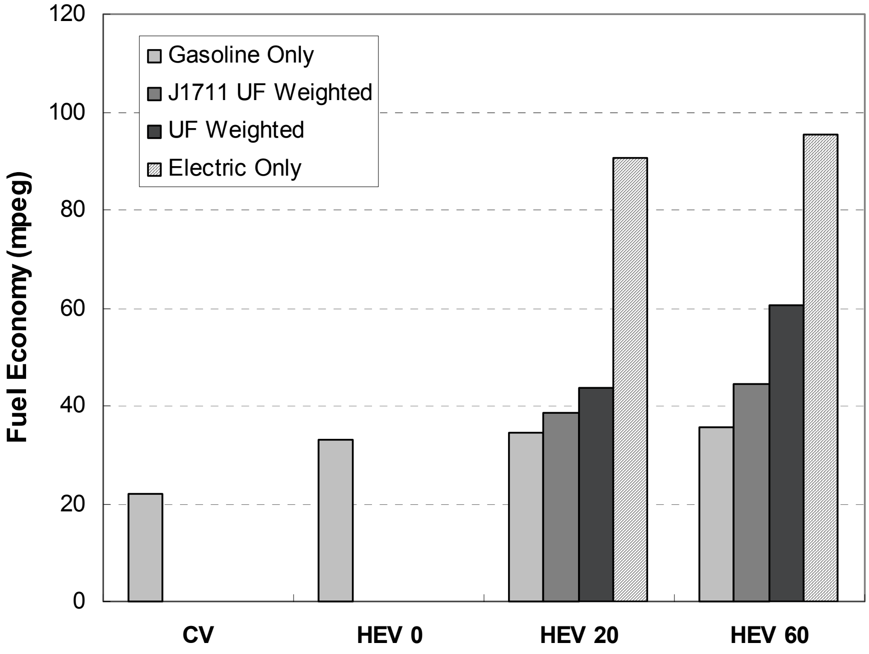

Figure 2-2
Fuel Economy Comparisons for the Mid-Size SUV

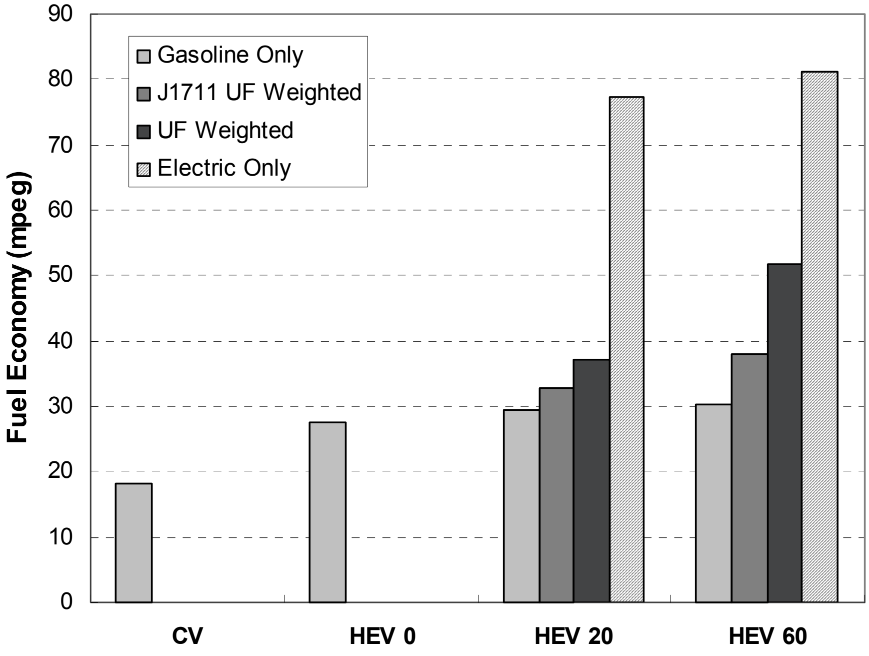

Figure 2-3
Fuel Economy Comparisons for the Full-Size SUV

Table 2-4
Mileage Weighted Probability Fuel Economies in miles per gasoline gallon equivalent

Vehicle	HEV 20	HEV 60
Compact Car	71.7	101.8
Mid-size SUV	46.6	68.8
Full-size SUV	39.8	58.7

None of the vehicles in this study used traditional non-hybrid methods of improving fuel economy, such as use of light-weight materials, improved aerodynamics, or low rolling resistance tires. This makes the above fuel economy values even more noteworthy.

Another metric of energy efficiency is based on the "total" energy used by a vehicle over its life that includes not only the propulsion "fuel" energy but all of the energy needed to produce the fuel used by a CV or HEV. This includes the energy needed to refine gasoline, and the energy needed to produce electricity. This total lifetime energy also is termed "fuel-cycle energy." Key assumptions underlying the fuel-cycle energies shown in Figure 2-4, 2-5, and 2-6 include the following:

- Gasoline includes methyl tertiary butyl ether (MTBE), an oxygenate made from natural gas
- Electricity used to charge plug-in HEVs is generated by combined cycle natural gas fired power plants, in the assumption that charging will be at night with electricity produced on the margin (additional electricity produced on top of the current electricity needs most likely will be produced by natural gas fired power plants; therefore, electricity production is allocated to natural gas. See more detailed fuel-cycle discussion in Reference 1).
- The energy used for fuel/energy production facility construction and vehicle construction is generally less than 15% of vehicle lifetime energy use.

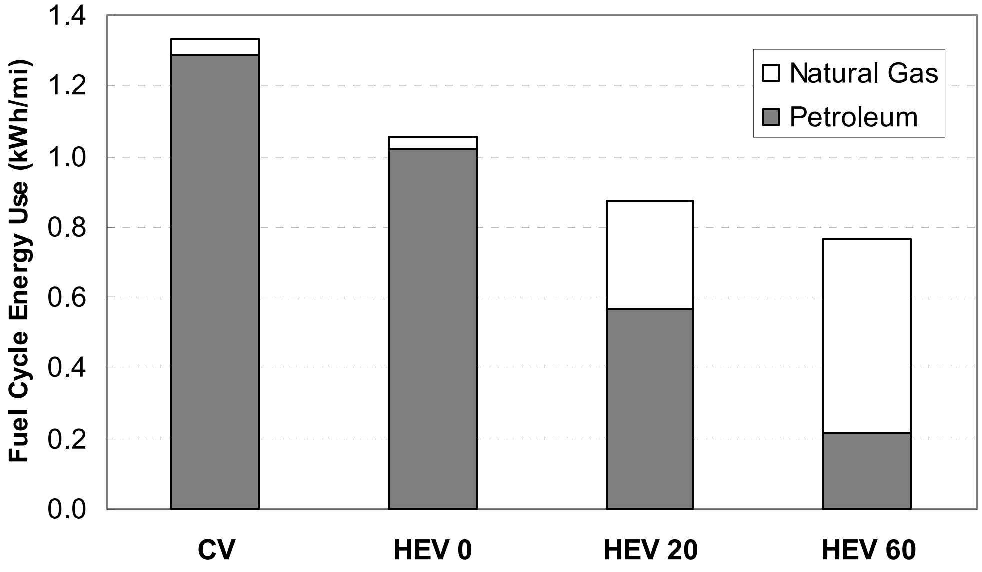

Figure 2-4
Full Fuel-cycle Energy Use for the Compact Car for the Average Driving Cycle and Charging Nightly

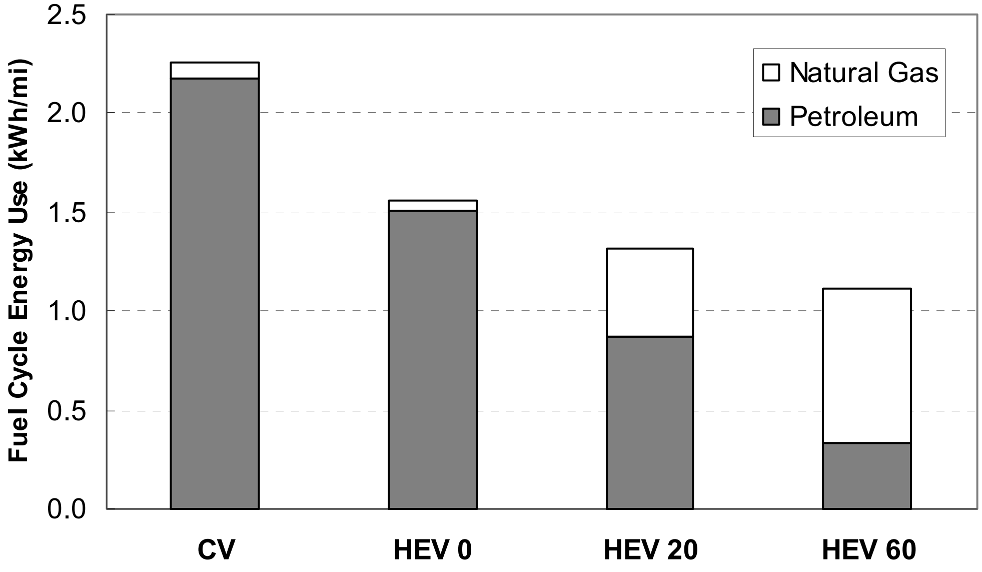

Figure 2-5
Full Fuel-cycle Energy Use for the Mid-Size SUV for the Average Driving Cycle and Charging Nightly

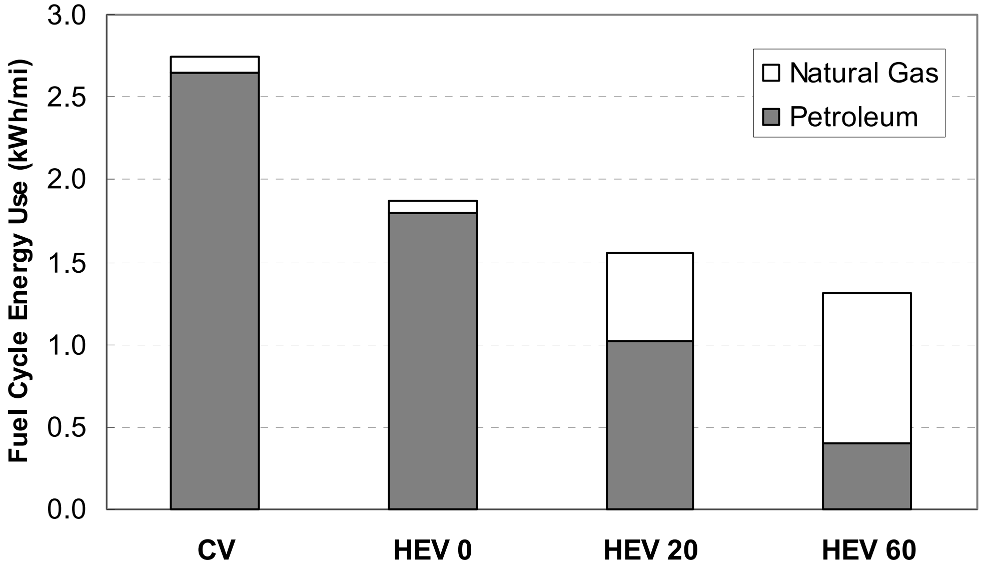

Figure 2-6
Full Fuel-cycle Energy Use for the Full-Size SUV for the Average Driving Cycle and Charging Nightly

2.5 Emissions

2.5.1 Methodology

Environmental impacts of HEVs were compared with each other and the baseline CV on the basis of emissions over the full fuel-cycle (“well-to-wheels”). This analysis takes into account all emissions associated with the extraction, processing, distribution, and final use of the energy used to propel the different types of HEVs, and compares them with those of the corresponding conventional vehicle. For the CV, these include all emissions that result from extracting crude oil, processing oil into a vehicle fuel, distributing the fuel, fueling the vehicle, and lastly, the vehicle’s tailpipe and evaporative emissions during operation. For the HEV 0, the perspective is the same because this type of vehicle only uses gasoline as fuel, although substantially less due to its higher efficiency. For plug-in HEVs like the HEV 20 and HEV 60, the “well-to-wheels” analysis must also take into account the emissions produced by the power plants that provide the electricity for charging the vehicles’ batteries. As shown below, fuel-cycle emissions can add up to a significant fraction of emissions associated with vehicle operation.

National impact of smog precursor (NO_x + HC) and greenhouse gas (primarily CO_2) emissions were examined for CVs and HEVs using the following assumptions:

- The HEVs and CVs meet California’s Super Ultra Low Emission Vehicle (SULEV) standards when operating on gasoline.
- Plug-in HEVs are charged primarily at night.

- Less efficient power generators, older coal and fuel oil power plants cannot readily be turned on and off, so these plants are used at full load during peak demand and idled or turned off at night; they do not respond to marginal load increases.
- Nuclear and hydroelectric power plants generally are already at capacity satisfying the base load requirement and thus not available to respond to marginal load increases.
- By 2010, many older fossil fuel power plants will have been replaced with new combined cycle turbines that have better efficiency, reduced emissions, and can respond efficiently to load changes.
- During off-peak periods (especially at night), marginal increases in power demand will be met by efficient combined cycle plants that can be dispatched more rapidly and economically than less efficient plants. Since charging even a substantial population of HEVs is estimated to be less than 1% of all power generated in 2010, power generated for HEV charging can be assumed to be on the generation margin and generated by high-efficiency, natural gas-fired combined cycle turbines.
- New power plants and refineries in non-attainment areas will need to meet the very low emission standards for "best available control technology" (BACT), without their owners/operators being able to claim emission offsets, particularly in California.
- Most oil refineries are at capacity; therefore, marginal gasoline use will most likely come from foreign oil. New refineries will be limited to BACT-level emissions, again without offsets.

For smog precursors (NO_x + HC), only urban emissions are considered since they directly affect non-attainment, and it is assumed that 70% of the emissions generated by power plants and refineries are in urban areas. Because CO_2 and other greenhouse gases emissions are persistent, they become globally distributed, and therefore, total CO_2 emissions need be considered. Further details on the emissions analysis used in this study can be found in Reference 1.

2.5.2 Results

Figures 2-7, 2-8, and 2-9 show totals of fuel-cycle, evaporative, and tailpipe emissions of urban smog precursors for compact, mid-size SUV, and full-size SUV CV and HEVs in milligrams per mile (mg/mi), respectively. It is evident that these emissions decrease with increasing degree of hybridization.

The fuel economy data assumed for this analysis are for "real world" driving as defined by the U.S.EPA, simulated by decreasing city and highway fuel economies calculated from this study's model by 10% and 22%, respectively[6]. A "real world" driving schedule (daily miles, annual miles, city/highway miles) was derived from the survey data discussed in Section 2.7 and is discussed in more detail in Reference 1.

---

[6] These factors are used by the U.S. Environmental Protection Agency in their Fuel Economy Guide and in vehicle labeling to represent "real world" driving. These factors were derived for CVs and may be different for HEVs but were used for this phase of the study.

CVs and all HEVs produce evaporative emissions from their fuel tanks and fuel systems. A zero emission standard, such as that required for partial ZEV (PZEV) credits, is a challenge for all vehicles. Plug-in HEVs that are operated on electric power for longer periods, however, might tend to emit higher evaporative emissions in real driving conditions. This is because the engine must be operating to ingest fuel vapor and thus purge the carbon canisters that are used to control evaporative emissions on vehicles. Methods to reduce evaporative emissions from hybrids clearly need more study. Generally, however, smog precursor emissions are lower for all HEVs due to their improved fuel economy, which results in less emissions at the gas station and refinery. Plug-in hybrids provide additional benefits because, on a gram per vehicle mile basis, emissions from electric power plants are much lower than that from the same vehicle running on gasoline.

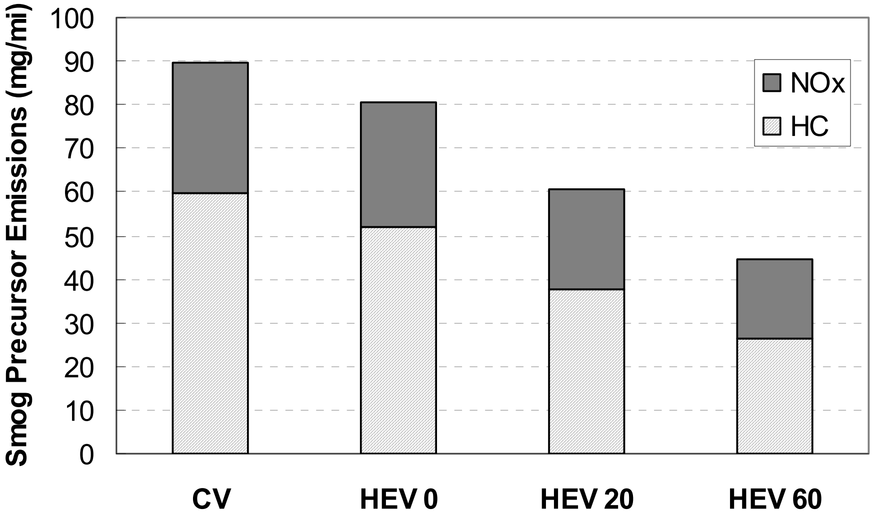

Figure 2-7
NOx Plus HC (Smog) "Well-to-Wheels" Emissions for the Compact Car for the Average Driving Schedule and Charging Nightly

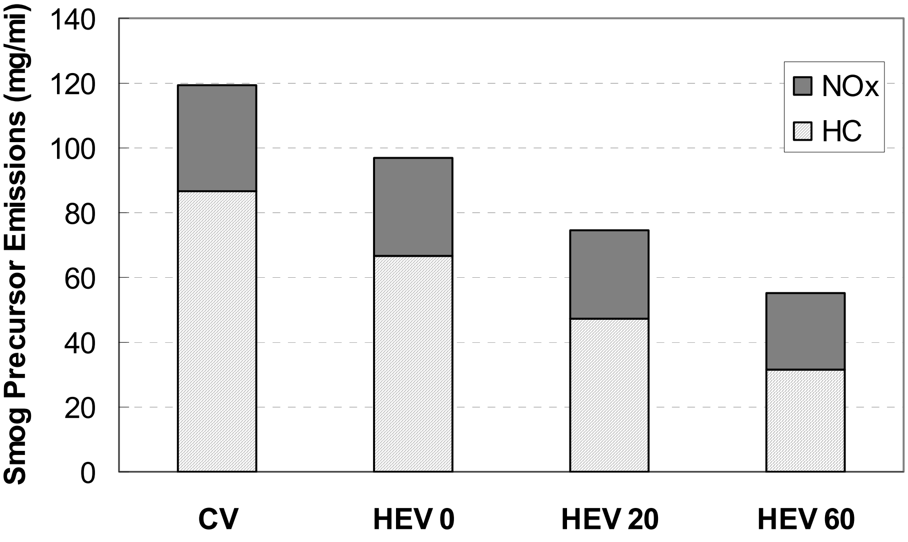

Figure 2-8
NOx Plus HC (Smog) "Well-to-Wheels" Emissions for the Mid-Size SUV for the Average Driving Schedule and Charging Nightly

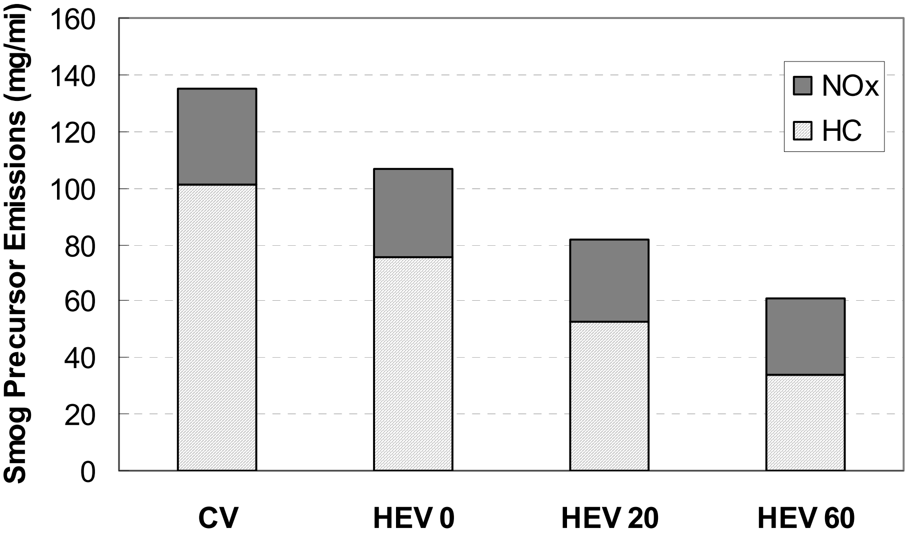

Figure 2-9
NOx Plus HC (Smog) "Well-to-Wheels" Emissions for the Full-Size SUV for the Average Driving Schedule and Charging Nightly

Figures 2-10, 2-11 and 2-12 show CO_2 emissions for the CV and HEV designs of the compact car, mid-size SUV, and full-size SUV, respectively. As shown by these figures, HEVs can substantially reduce greenhouse gas emissions due to their improved fuel economy alone, and these benefits grow with increasing all-electric range and its utilization. In addition, greenhouse gas emissions from power plants on a gram per all-electric vehicle mile are much lower than greenhouse refinery emissions on a gram per gasoline vehicle mile.

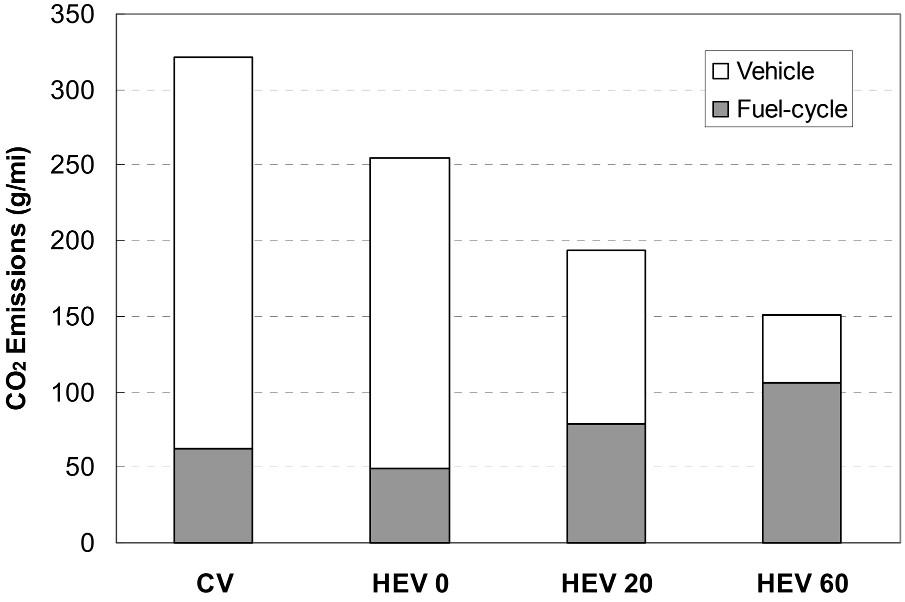

Figure 2-10
Greenhouse Gas Emissions (CO_2) "Well-to-Wheels" for the Compact Car for the Average Driving Schedule and Charging Nightly

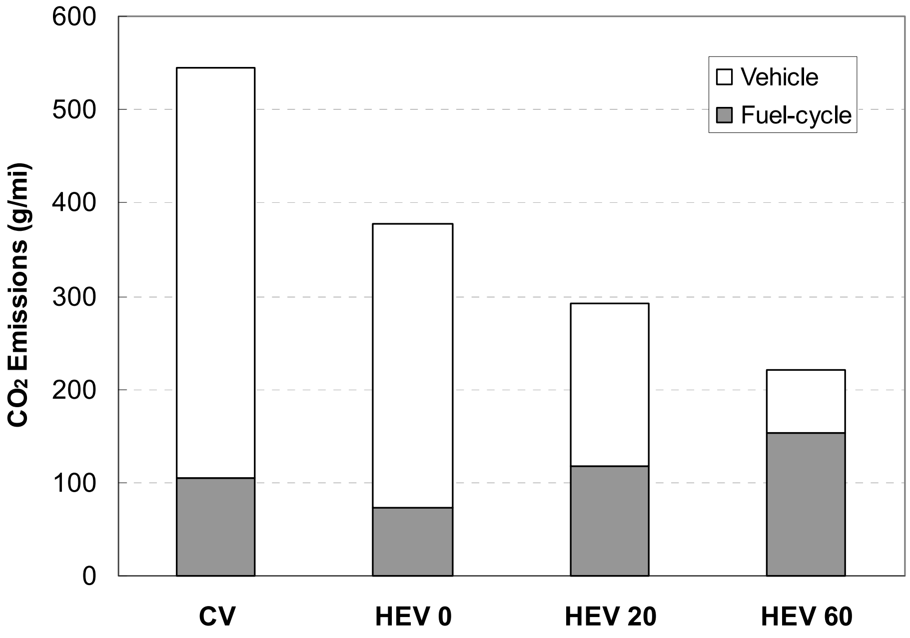

Figure 2-11
Greenhouse Gas Emissions (CO_2) "Well-to-Wheels" for the Mid-Size SUV for the Average Driving Schedule and Charging Nightly

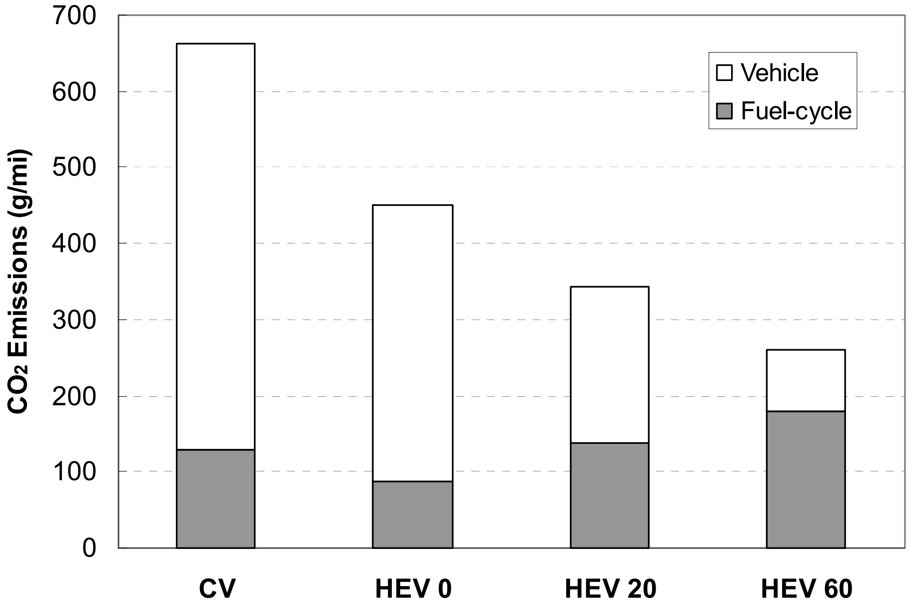

Figure 2-12
Greenhouse Gas Emissions (CO_2) "Well-to-Wheels" for the Full-Size SUV for the Average Driving Schedule and Charging Nightly

2.6 Vehicle Retail Price Equivalent and Operating Costs

2.6.1 Vehicle Retail Price Equivalent

Many factors and considerations—including proprietary information and pricing strategies not available to the WG—enter into the determination of a manufacturer's suggested retail price (MSRP) for a presently marketed vehicle. Thus, projecting likely MSRPs for future vehicles such as the HEVs modeled in this study would not have resulted in meaningful numbers for the vehicle cost comparisons. Instead, the WG used the vehicle ”Retail Price Equivalent” (RPE) as the basis for estimating and comparing the costs of hybrids and the corresponding conventional vehicles.

For the purpose of this study, a vehicle's RPE is defined as the sum of all component costs, marked-up with the applicable manufacturer and dealer overheads and profits, as explained in more detail below

2.6.1.1 Methodology

Two different methodologies were used to estimate vehicle RPEs. In the first method, component costs were estimated as the cost of labor and materials for each component. In the second method, component costs were estimated to be the cost that a manufacturer would pay to build the component or, in the case of electric components (motor, controller, and battery), buy it from a supplier. The first method is a typical automobile industry standard accounting procedure that was adopted as the "Base Method" by the WG; the second was developed by Argonne National Laboratory (ANL) with input from the WG. The WG inputs were not based upon proprietary information from members of the WG.

Component cost estimates were collected from a number of credible sources and checked against or supplemented by the WG's own estimates where necessary. Generally, these estimates or extrapolations took into account technological advancements that could be foreseen or considered likely to occur by the year 2010 and that applied in mass production, for example, at production volumes of 100,000 vehicles per year. All costs are stated in year 2001 dollars[7].

In the Base Method, all component costs are treated as the cost of labor and materials. Manufacturer and dealer mark-ups are applied to all component costs. Costs for vehicle development are also added. In the ANL method, electric components (motor, controller, and battery) are assumed to be supplied by outside vendors. Their costs include not only the cost of labor and materials, but also a partial mark-up that includes some research and development costs, supplier overhead and profit, and appropriate warranties. Different mark-ups are applied to component costs depending on whether they are built by the manufacturer or supplied by a supplier. A single mark-up covers manufacturer and dealer mark-ups and development costs.

---

[7] The mid-size car study in Reference 1 was stated in year 2000 dollars. The consumer price index for new car purchases changed less than 1 percent between 2000 and 2001.

Both methods assume that batteries are one of the largest cost components and therefore a reduced mark-up is applied[8]. Mark-up factors for the two methods are given in Table 2-5; more detail on the two methods can be found in Reference 1. Details of component costs for the three vehicle platforms can be found in the Appendix.

Glider costs are determined by subtracting CV component costs from the CV MSRP. CV MSRPs for the three platforms were determined from the Kelly Blue Book website (www.kbb.com) and are listed in the Appendix.

Table 2-5
Summary of the Base and ANL Methods

Item	Base Method	ANL Method
Component Costs	Assumes all costs are manufacturer costs for labor and materials	Same cost as Base Method, except it assumes that motor, controller and batteries already have a partial mark-up from supplier.
Manufacturer Mark-up	All component costs except battery modules are marked-up at 1.5 times component cost[a]	All components manufactured by the vehicle manufacturer are marked-up at 2 times component costs, those purchased from an outside vendor are marked-up at 1.5 times component costs.[a]
Battery Module Mark-up	Battery module mark-ups are 50% of battery module costs not to exceed $800 for the HEV 0 battery, $850 for the HEV 20 battery, and $900 for the HEV 60 battery.	Same as Base Method.
Dealer Mark-up	All components carry an additional mark-up of 16.3% of manufacturer marked-up prices.	Included in manufacturer mark-up
Development costs	Development costs for 2010 component technology (amortized over 5 years of production) are added at $94 per vehicle for the CV, $440 for the HEV 0, and $464 for the HEV 20 and HEV 60.	Included in manufacturer mark-up

[a] It is likely that the mark-up will be different for compact cars compared to SUVs, however, due to lack of data, a standard mark-up was used.

2.6.1.2 Discussion of Results

Component- and vehicle-level retail price equivalent (RPE) estimates for the compact car CV and HEVs are compared in Figure 2-13. Similar charts are shown for the mid-size SUV in Figure 2-14 and the full-size SUV in Figure 2-15. For each of the vehicles, the bars represent the numerical averages of the component RPEs determined using the Base and ANL methods. These figures make clear that most of the cost increments between the HEV designs and the CV are due to battery pack and charger costs.

---

[8] This approach was very controversial within the WG due to the concern for potential uncertain additional costs. More details are given in Reference 1.

Total RPEs for the CV and hybrid vehicles are shown separately for the Base and ANL methods in Figures 2-16, 2-17, and 2-18 for the compact car, mid-size SUV, and full-size SUV, respectively. Depending on the method used, compared to the compact CV RPE, the compact HEV 0 RPE is approximately $2,500 to $3,600 higher, the compact HEV20 RPE approximately $4,500 to $6,100 higher, and the compact HEV 60 RPE is approximately $8,100 to $10,300 higher. Similarly, the mid-size SUV HEV 0 RPE is approximately $4,000 to $5,500 higher than the mid-size SUV CV, the mid-size SUV HEV 20 RPE approximately $6,400 to $8,500 higher, and the mid-size SUV HEV 60 is approximately $10,100 to $13,100 higher. The full-size SUV HEV 0 RPE is approximately $4,500 to $6,300 higher than the full-size SUV CV, the full-size SUV HEV 20 RPE approximately $6,000 to $8,500 higher, and the full-size SUV HEV 60 is approximately $11,000 to $14,500 higher. The cost premiums for compact HEVs would be increased by about $420 if future year conventional compact vehicles are assumed to use more economical continuously variable transmissions (CVTs). The SUV HEVs use an automatically shifted manual transmission, since CVTs are not currently available in sizes needed for SUVs.

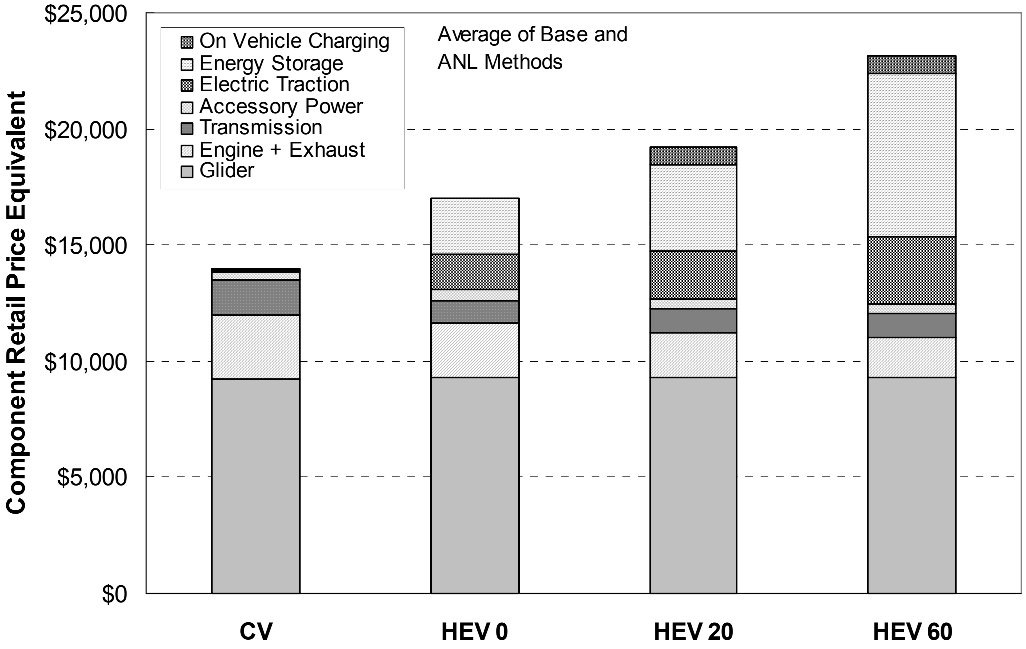

Figure 2-13
Compact Car Component Retail Price Equivalent

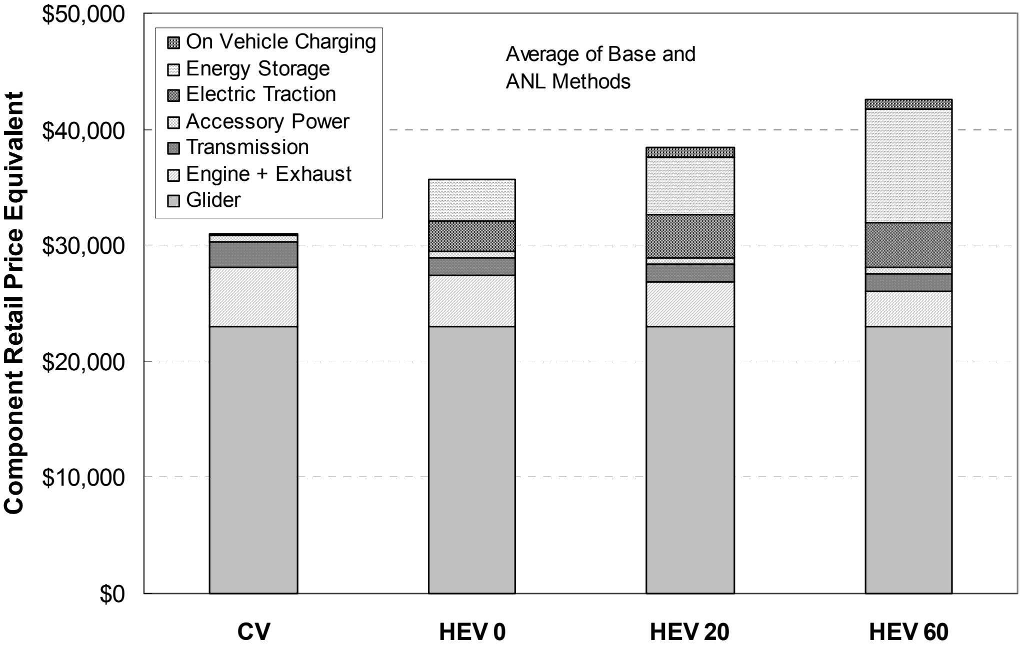

Figure 2-14
Mid-size SUV Component Retail Price Equivalent

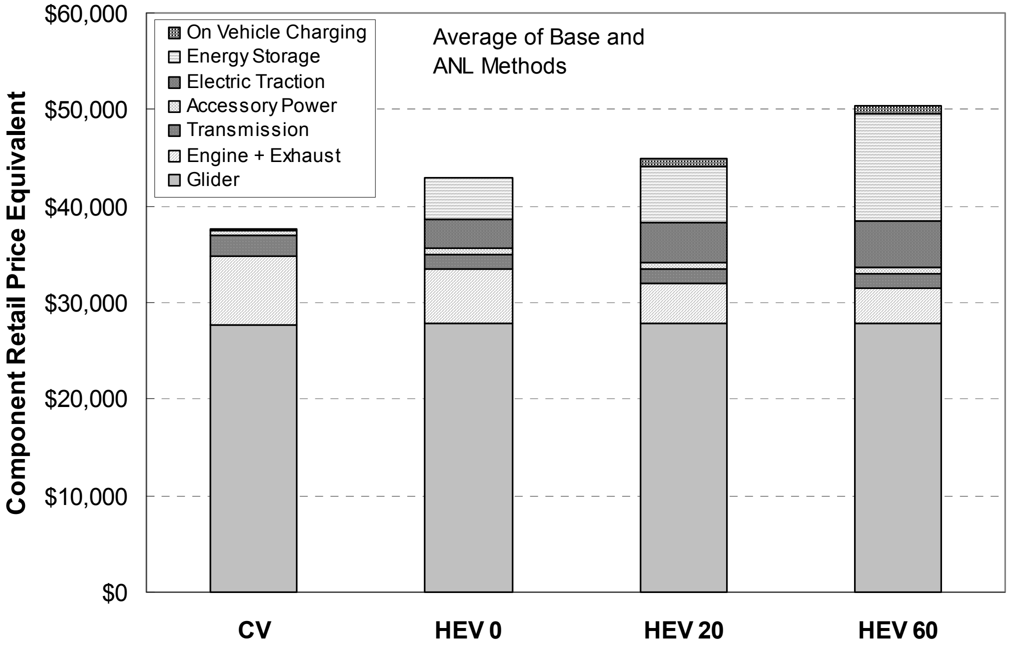

Figure 2-15
Full-size SUV Component Retail Price Equivalent

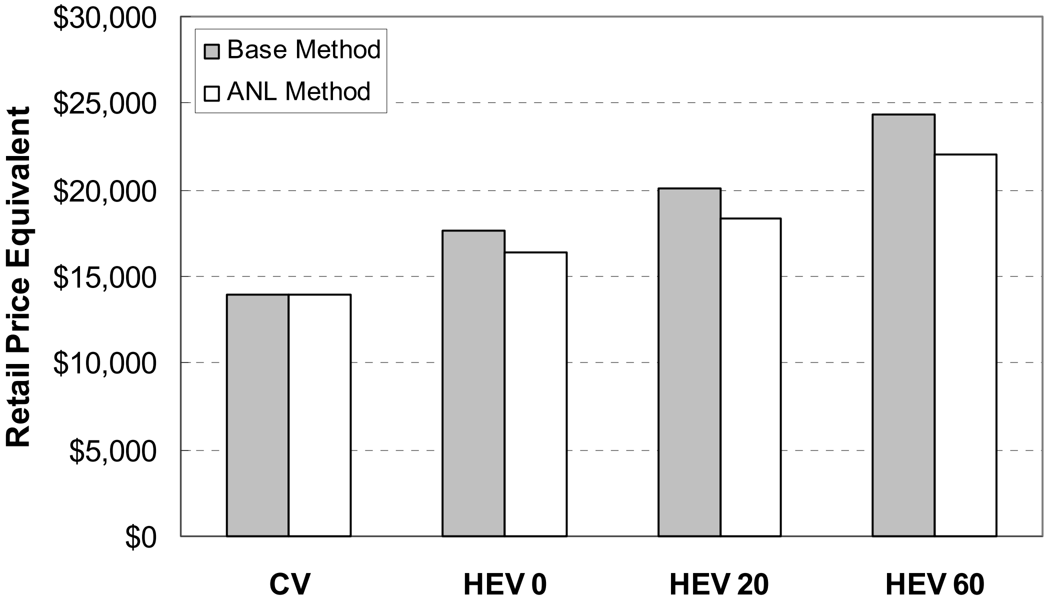

Figure 2-16
Retail Price Equivalents for the Compact Car

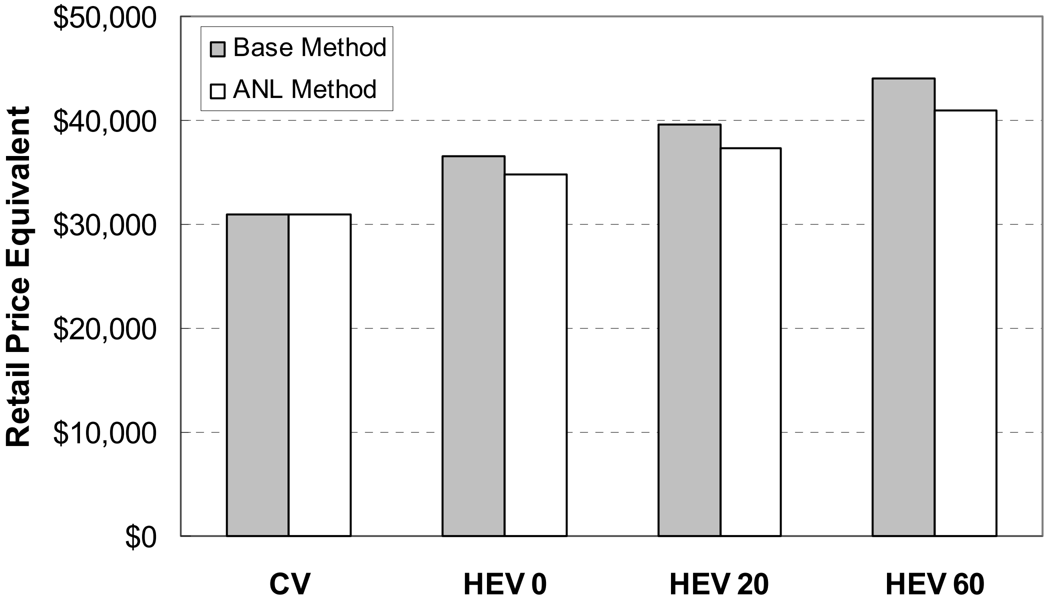

Figure 2-17
Retail Price Equivalents for the Mid-size SUV

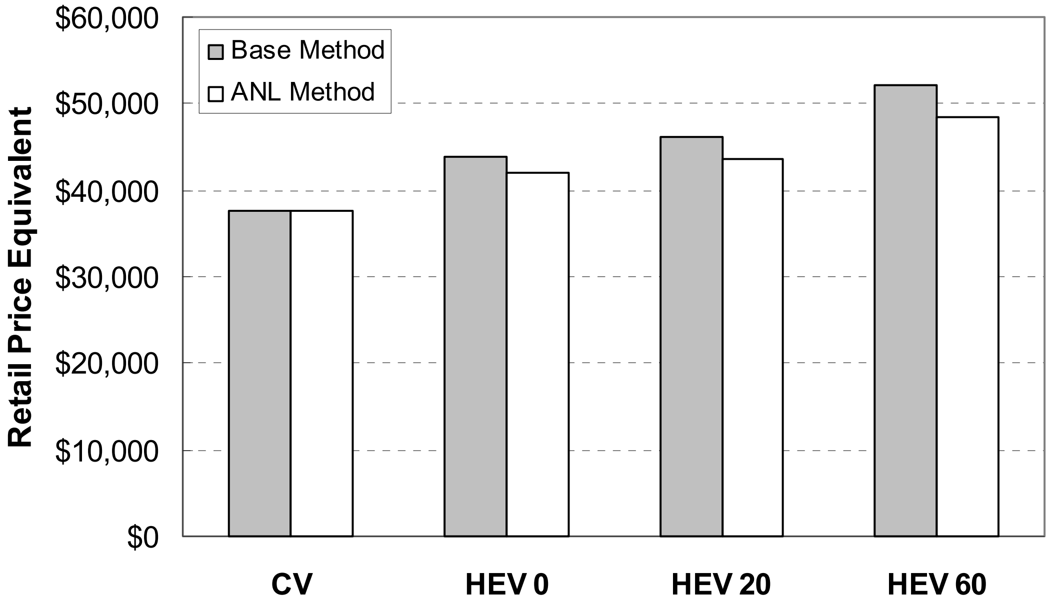

Figure 2-18
Retail Price Equivalents for the Full-size SUV

An additional cost of $1000 for an infrastructure upgrade could be necessary for charging the mid-size and full-size SUV HEV 60 if a 240V 40-amp circuit is required to be installed[9].

Significant uncertainties exist in overall vehicle RPE because of uncertainties in future costs of mass-produced batteries that are presently produced only in limited volume. The uncertainties increase with the increasing contribution of the battery to vehicle costs as battery capacity increases from the HEV 0 to HEV 60. To put the battery costs in perspective, the lowest specific cost for NiMH electric vehicle battery modules is estimated to be $225 to $250 per kWh in mass production and unlikely to decrease without major, currently-unforeseen materials breakthroughs during the next decade [5]. Even less information is available publicly on HEV battery module costs, so the WG had to develop its own first-cut estimate from EV battery module costs, allowing for the generally higher specific costs of battery designs of a given chemistry as specific power increases and specific energy decreases as a result. Since in large production volume, battery costs are largely driven by material cost, they were estimated in this study by assuming that, for a given battery type and chemistry, specific costs (in $/kWh) are inversely proportional to their specific energy (W/Wh). The battery module cost curve shown in Figure 2-19 was developed by Kalhammer for the WG and confirmed by a NiMH battery developer. (See Reference 1 for more details on battery module costs and the Appendix for specific battery power to energy ratios and costs.)

---

[9] Some utilities use a time-of-use (TOU) meter to obtain lower electricity prices (like the $0.06/kWh estimated in this study), which adds an additional $235 for installation of such a meter. At least one utility does not use a TOU meter for the lower rates (which can be linked to ownership or miles traveled).

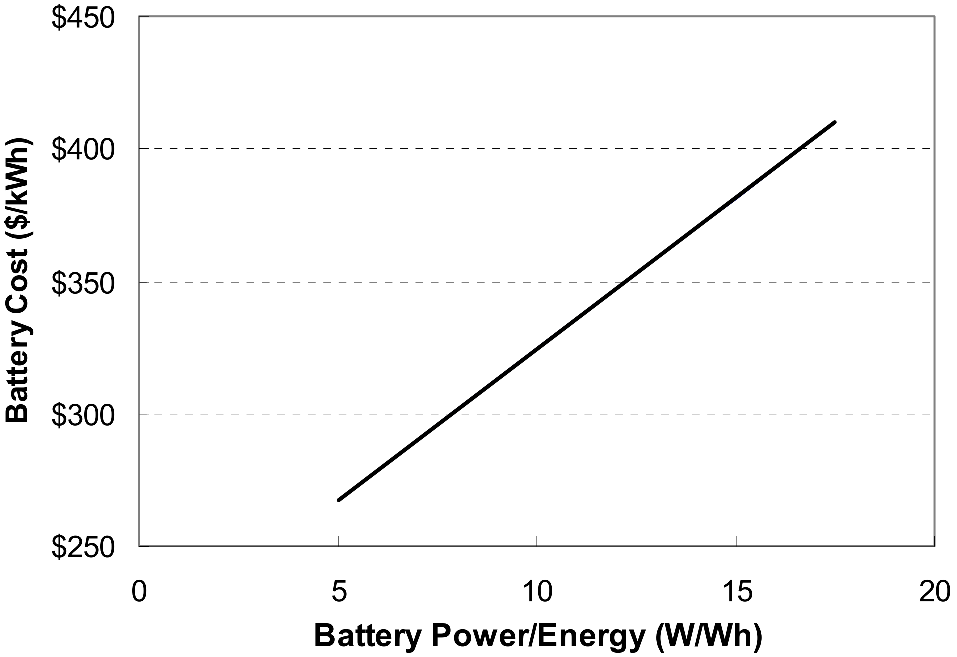

Figure 2-19
NiMH Battery Module Costs to OEM Versus Battery Energy

2.6.2 Operating Costs

2.6.2.1 Methodology

Operating costs include costs for fuel and maintenance. In this study, both cost contributions were calculated using label-adjusted fuel economies and representative driving patterns based on survey results. The annual mileage for the average driving pattern is 13,322 miles per year. Further discussion of the methodology can be found in Reference 1.

Fuel costs were assumed to be $1.65 per gallon of gasoline and $0.06 per kWh of electricity. The gasoline price was the average national gasoline price at the time of the study; the kWh price was the average price of off-peak electricity currently offered by utilities (Boston, Atlanta, Phoenix, Los Angeles, and San Francisco) for charging of EVs[10].

Scheduled maintenance costs were estimated from the annual distances driven with engine and battery power, respectively. Further discussion of the methodology used for estimating scheduled maintenance costs can be found in Reference 1.

---

[10] The report assumes that in 2010, electric fueled vehicles would continue not to pay road taxes used by federal and state governments (for roads and transit) and that gasoline fueled vehicles would continue not to pay electric utilities users tax (0-12%) used by some local and state governments (for police, fire, libraries, etc).

2.6.2.2 Discussion of Results

Average fuel costs per mile for the compact CV and HEVs are shown in Figure 2-20; the mid-size SUV and full-size SUV average fuel costs are shown in Figures 2-21 and 2-22, respectively. The analysis assumes that the plug-in HEVs are charged fully every night. The figures show that fuel costs for hybrid vehicles, particularly plug-in HEVs, are significantly lower than for the conventional vehicle. For example, if one applies the assumptions and estimates developed in this analysis, a compact HEV 60 driver can save over $377 in fuel costs per year over a comparable CV if the vehicle is plugged in and charged fully on a daily basis, while a mid-size SUV owner can save $705 and a full-size SUV owner can save $876 over the equivalent CV. On the same basis, an compact HEV 0 would save approximately $240 per year, a mid-size SUV HEV 0 would save $350, and a full-size SUV HEV 0 would save $444, over that for an equivalent CV. It should be noted, however, that a portion of the fuel cost savings results from the decision to assume unequal taxation for gasoline and electricity. Collecting road tax on electricity would reduce the assumed fuel cost advantage for HEVs.

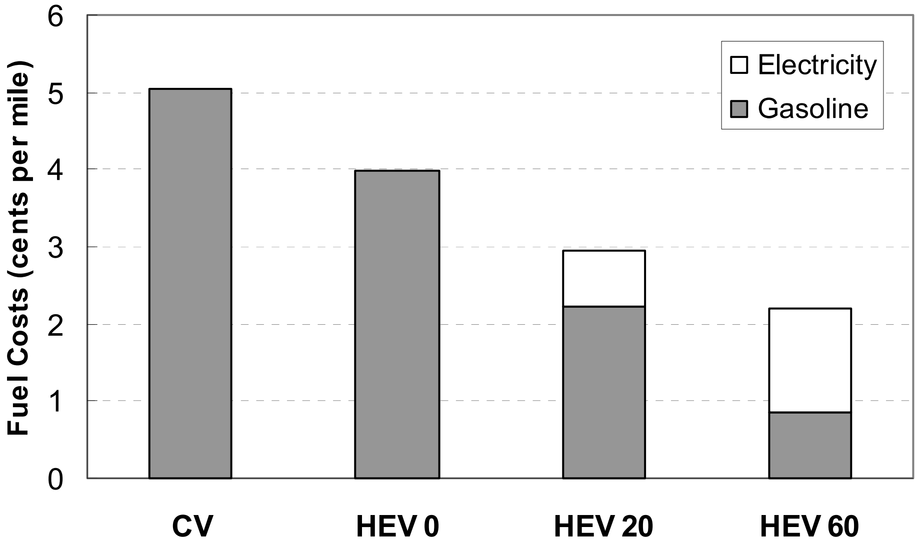

Figure 2-20
Fuel Costs Per Mile for the Compact Car When Charging Nightly

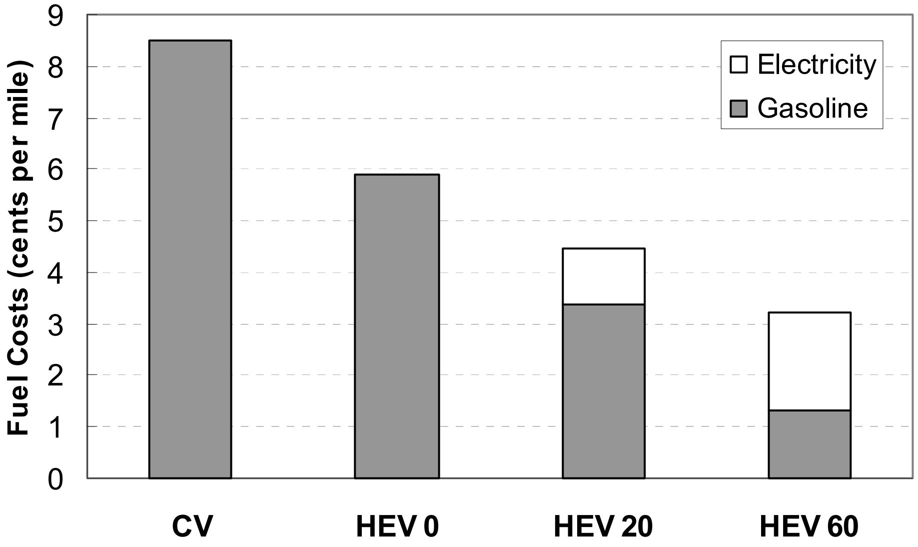

Figure 2-21
Fuel Costs Per Mile for the Mid-size SUV When Charging Nightly

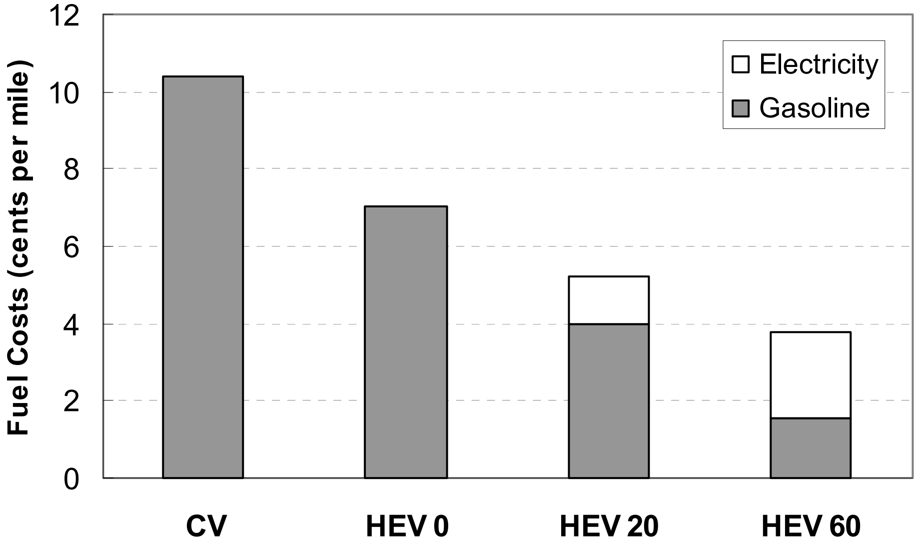

Figure 2-22
Fuel Costs Per Mile for the Full-size SUV When Charging Nightly

The vehicle maintenance costs considered in this analysis are also predicted to be lower for HEVs. Based upon the assumptions and analysis used in this study, compared to an equivalent conventional vehicle, a compact HEV 60 could save its user around $120 per year in scheduled maintenance costs if the vehicle is plugged in and charged fully every night to maximize electric-only operation, while a mid-size SUV HEV 60 could save $140 and a full-size SUV HEV 60 could save $151 in annual scheduled maintenance costs over the comparable CV if plugged in and charged fully each night.

2.6.2.3 Battery Charging Times and Charger Requirements

To charge the batteries of a HEV 20 or HEV 60 from the electric power grid, a charger must convert AC power from the grid to DC at the correct battery voltage (typically 150-300V), and must also control the rate and end of charging to prevent excessive overcharging. To prevent electrical hazard to the user, chargers require a ground fault circuit interrupt (GFCI) function. Currently, inductive and conductive charging systems are in use. In conductive charging, electricity from the grid is transferred through a conducting connection to the charger that can be located off-board or on-board the HEV. For inductive charging, a paddle-like inductor terminates the power cord. This paddle is inserted into the vehicle where the inductor generates a magnetic field inside a transformer that in turn, induces a current in the current pick-up on the vehicle. This study assumed conductive charging with an on-board charger.

Charging time for HEVs depends upon the battery size and charger circuit used. As shown in Table 2-6, all three HEV 20 platforms can be charged in less than 8 hours with a 120 V, 15A charger. The compact HEV 60 battery can be charged from empty in less than 10 hours (e.g., overnight) with a 120 V, 20 A charger, so all HEV 20s and the compact HEV 60 can come standard with a 120 V cord. Both SUV HEV 60s, however, will require a 240 V, 40 A charger to charge overnight[11]. Faster charging is also possible for the HEV 20s and the compact HEV 60 with a 240 V 40 A charger such as might be available at public EV charging stations. The WG estimated the cost of installing an additional 120V, 20 A circuit and outlet near the electrical panel of a residential or commercial building (or upgrading an existing 15 amp circuit) at $200 and the cost of adding a 240V 40 A circuit at $1,000[12].

There are infrastructure issues that have been identified which affect some customers. These include 15 amp versus 20 amp circuit breakers and multiple GFCIs in series issues. These infrastructure issues will need to be addressed and are dependent upon the final design of the vehicle.

---

[11] It should be noted that it is unlikely that an HEV 60 will be fully discharged during a given travel day. Thus charging times from a higher SOC to full capacity will be shorter if charged nightly.

[12] In addition, some utilities use a time-of-use meter to obtain lower electricity prices (like the $0.06/kWh estimated in this study), which adds an additional $235 for installation of such a meter. At least one utility does not use a TOU meter for the lower rates (which can be linked to ownership or miles traveled).

Table 2-6
Charging Time for Various Circuit Voltage and Amperage Levels

Charging Circuit	Charger Size[a]	Charging Rate[b]	Infrastructure Costs	Charging Time (To Charge Empty Pack[c]) HEV 20	Charging Time (To Charge Empty Pack[c]) HEV 60
Compact Car					
Pack size	—	—		5.1 kWh	15.5 kWh
Rated pack size[d]	—	—		4.1 kWh	12.4 kWh
120 V 15 amp	1.4 kW	1.0 kWh/hr	$0	4.0 hrs	12.3 hrs
120 V 20 amp	1.9 kW	1.3 kWh/hr	$200	3.0 hrs	9.2 hrs
240 V 40 amp	7.7 kW	5.7 kWh/hr	$1,000	0.7 hrs	2.2 hrs
Mid-size SUV					
Pack size	—	—		7.9 kWh	23.4 kWh
Rated pack size[d]	—	—		6.3 kWh	18.7 kWh
120 V 15 amp	1.4 kW	1.0 kWh/hr	$0	6.3 hrs	18.6 hrs
120 V 20 amp	1.9 kW	1.3 kWh/hr	$200	4.7 hrs	14.0 hrs
240 V 40 amp	7.7 kW	5.7 kWh/hr	$1,000	1.1 hrs	3.3 hrs
Full-size SUV					
Pack size	—	—		9.3 kWh	27.7 kWh
Rated pack size[d]	—	—		7.4 kWh	22.1 kWh
120 V 15 amp	1.4 kW	1.0 kWh/hr	$0	7.4 hrs	22.1 hrs
120 V 20 amp	1.9 kW	1.3 kWh/hr	$200	5.6 hrs	16.5 hrs
240 V 40 amp	7.7 kW	5.7 kWh/hr	$1,000	1.3 hrs	3.9 hrs

[a] An 80% required safety factor for continuous charging is used.

[b] Charger efficiency assumed to be 82% for 120 V chargers and 87% for 240 V chargers

[c] Battery efficiency assumed to be 85%.

[d] Rated pack size assumed to be 80% of nominal pack size.

2.6.2.4 Battery Replacement and Its Costs

Like all secondary batteries, HEV batteries will degrade in both shallow and deep cycling. Thus, a key question in the WG's vehicle cost analysis was whether—and, if so, how often—the different hybrid electric vehicles' batteries would have to be replaced over the nominal life of the vehicle, at least 100,000 miles or 10 years of driving. These questions, and the costs associated with battery replacement, are discussed below.

As discussed in Reference 1, HEV 0 NiMH batteries very likely will deliver sufficient shallow cycles for the 100,000-mile vehicle lifetime, and HEV 60 NiMH batteries should be able to deliver the deep cycles required for 100,000 vehicle miles. HEV 20 batteries, because of their smaller capacity, will undergo substantially more deep cycles and, therefore, might require replacement within the 100,000-mile lifetime under conditions that maximize all-electric HEV operation. Several methods to extend HEV 20 battery are discussed in Reference 1. The consumer cost of battery replacements is shown in Table 2-7 if the batteries have a salvage value (see Reference 1).

Table 2-7
Approximate Battery Replacement Costs to Consumers[a]

Vehicle Platform	HEV 0	HEV 20	HEV 60
Compact Car	$1,200 to $1,400	$1,800 to $2,600	$4,100 to $6,400
Mid-size SUV	$1,900 to $2,600	$2,800 to $4,100	$6,200 to $9,800
Full-size SUV	$2,500 to $3,500	$3.500 to $5,300	$7,100 to $11,500

[a] Cost variation represents two different cost methods discussed in Reference 1.

If vehicle lifetimes were extended to 15 years or 150,000 miles, it is likely that all HEV designs will require battery replacements within this extended vehicle lifetime. However, this depends upon the vehicle control strategy and as well as many other factors. In addition, larger battery packs tend to provide more all-electric miles over their lifetimes than smaller battery packs.

After the batteries degrade to the 80% of original capacity, the emissions and fuel costs of a plug-in hybrid will slowly approach the emissions and fuel costs of an HEV 0 if the batteries are not replaced. However, unlike an EV, plug-in hybrids are still quite functional without a battery replacement with the proper control strategies. At present it is unknown when degraded battery capacity will affect performance.

2.7 Customer Preference

Customer preference for HEVs was studied using two methods. The first used focus groups to determine how potential buyers viewed HEVs. In the second, a 400-person survey was used to develop a choice based market model. These methods are described below. Further details can be found in Reference 1.

2.7.1 Focus Groups

Four focus groups were conducted in Los Angeles and Orlando to determine what features of HEVs customers found most interesting and how best to explain HEV concepts. Focus groups were conducted by gathering impressions, educating the participants, and through guided discussions. Focus group participants were told to assume that HEVs had been sold for 5 or more years and that they were as safe, reliable, and had the same performance as conventional vehicles.

The focus groups indicated that, provided the basic assumptions are met, most participants preferred an HEV to a conventional vehicle if the HEV was available in the same design and at the same vehicle price. Participants thought fuel cost savings were one of the most attractive features of HEVs. Although environmental benefits, fewer trips to the gas station, and the flexibility of the dual-mode operation were influential in purchasing a vehicle, few respondents were willing to pay more for these attributes.

A large majority of the participants thought that plugging in was preferable if it was convenient, but some had issues regarding charging. Most people considered plugging in their vehicles more convenient than fueling at a gasoline station. Further discussion on the Focus Groups can be found in Reference 1.

2.7.2 Choice Based Market Model

A computer-administered quantitative customer preference interview was taken by over 400 consumers in Boston, Atlanta, Phoenix, and Los Angeles. The first portion of the interview contained over 60 trade-off questions for nine independent attributes of HEVs, which were later linked to describe the HEV 0, HEV 20, and HEV 60. Additional trade-off questions were also asked comparing HEV designs to each other and to the consumer's conventional vehicle. The results from these questions were used to construct a choice based market model (CBMM). This model was then used to predict market potential or preference for HEVs. The interview also included over 100 direct assessment questions to measure demographics and attitudes as well as customer views on HEV benefits, government incentives, and plugging in versus going to the gasoline station. Further description of the CBMM can be found in Reference 1.

Results from the CBMM for four vehicle price scenarios are shown for the compact car in Figure 2-23, the mid-size SUV in Figure 2-24, and the full-size SUV in Figure 2-25[13]. The Base and ANL prices are those described in Section 2.6.1. The Low and High price scenarios represent possible price uncertainty in vehicle prices[14]. The Low and High prices are relative to the Base price and represent incremental costs that are 50% less or 50% greater than the difference between the Base price HEV and the Base price CV. Actual prices used in this analysis can be found in the Appendix.

As shown in these figures, market potential is very sensitive to vehicle price. At the Low vehicle price, the HEV 20 is preferred over the HEV 0, and HEV 60 in all platforms. At the Low vehicle price, the HEV 0 and the HEV 20 are preferred over the CV in the full-size SUV category. At the ANL, Base, and High prices, the HEV 0 and HEV 20 are preferred over the HEV 60 in all platforms.

Fuel price also had a significant effect on market potential. If gasoline prices rose from $1.65 per gallon (baseline assumption) to $3.00 per gallon (an 82% increase), market potential for HEVs would also increase as shown in Figure 2-26 for vehicles using the Base Price scenario and Figure 2-27 using the ANL Price scenario. As shown by those figures, a very dramatic increase in customer preference for the HEV 60 occurred when gasoline prices are raised. In fact, full size

---

[13] The results assume a simple market (HEV 0 versus CV, HEV 20 versus CV, and HEV 60 versus CV).

[14] The High price case might occur if, for example, production volumes are less than the 100,000 units per year estimated in this study, if battery costs are significantly higher, or the selling costs of HEVs exceed those of CVs. The Low price case might occur if government incentives reduce the vehicle price or if production and selling costs are not used to determine price. Also, some components costed in this analysis could be used in other product lines, so component costs could be lower than represented here. It should be noted that the "High" and "Low" prices do not necessarily bound all possible outcomes. These scenarios were not based upon proprietary input from members of the WG.

SUV HEV 0 and HEV 20 are preferred over the CV at the base price and the mid-size SUV HEV 0 and HEV 20 and all the full-size SUV HEVs are preferred over the CV at the ANL price.

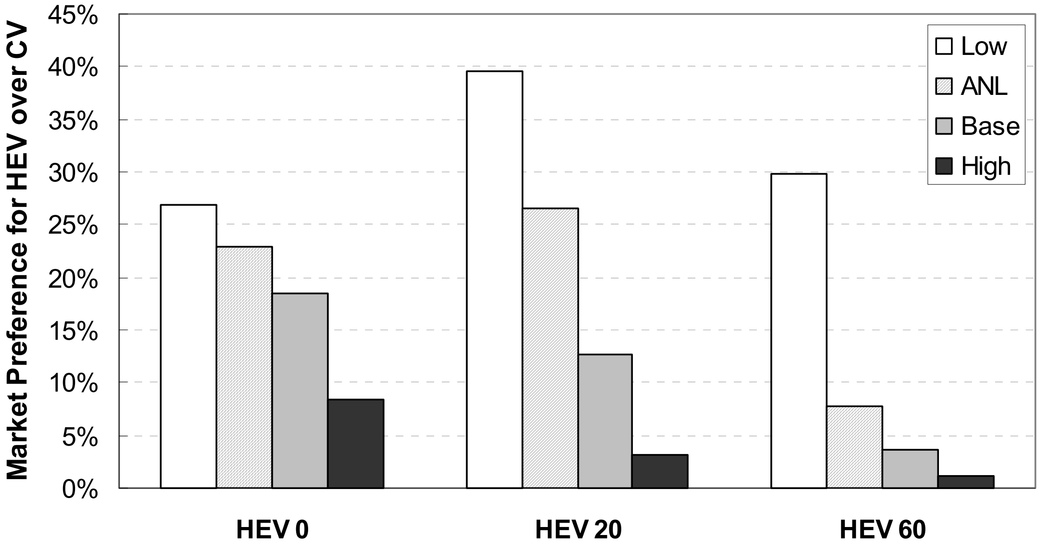

Figure 2-23
Market Preference versus Vehicle Price for Compact HEVs

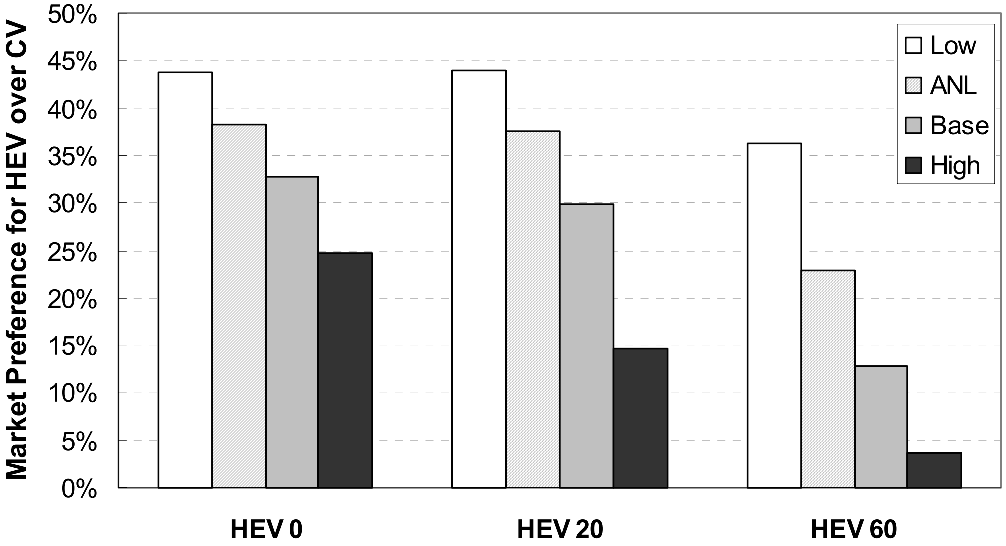

Figure 2-24
Market Preference versus Vehicle Price for Mid-size SUV HEVs

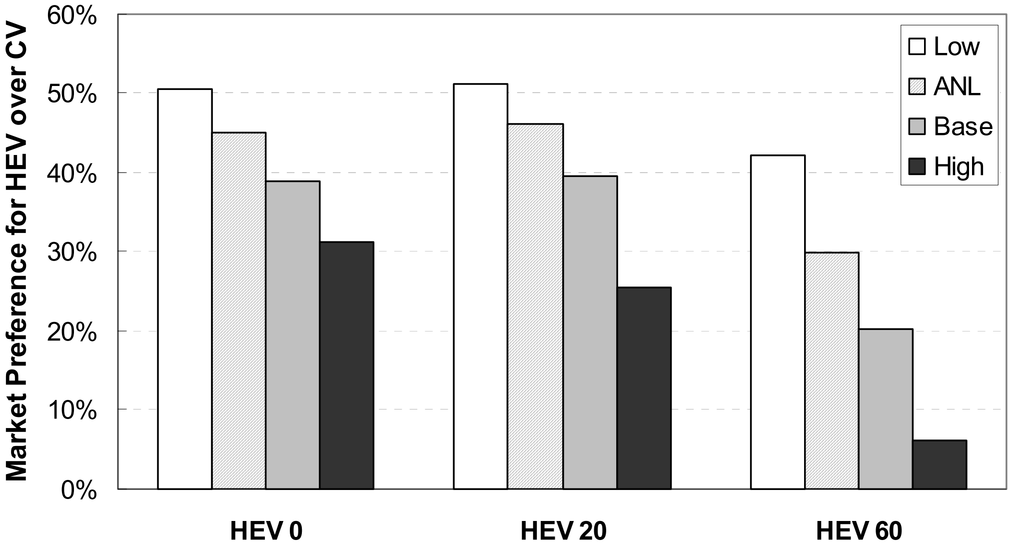

Figure 2-25
Market Preference versus Vehicle Price for Full-size SUV HEVs

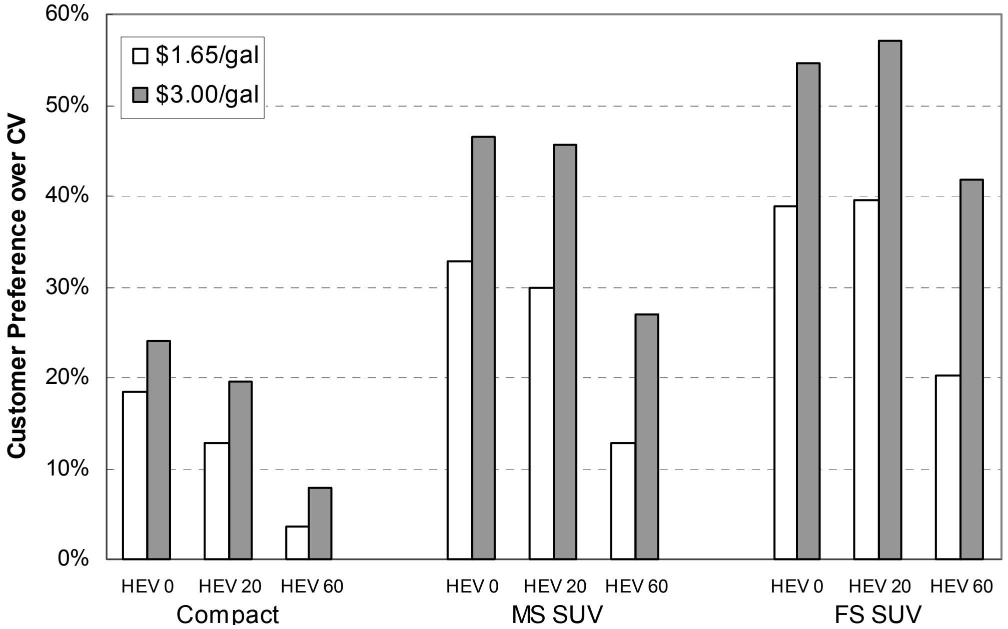

Figure 2-26
Market Preference versus Gasoline Price at the Base Vehicle Price

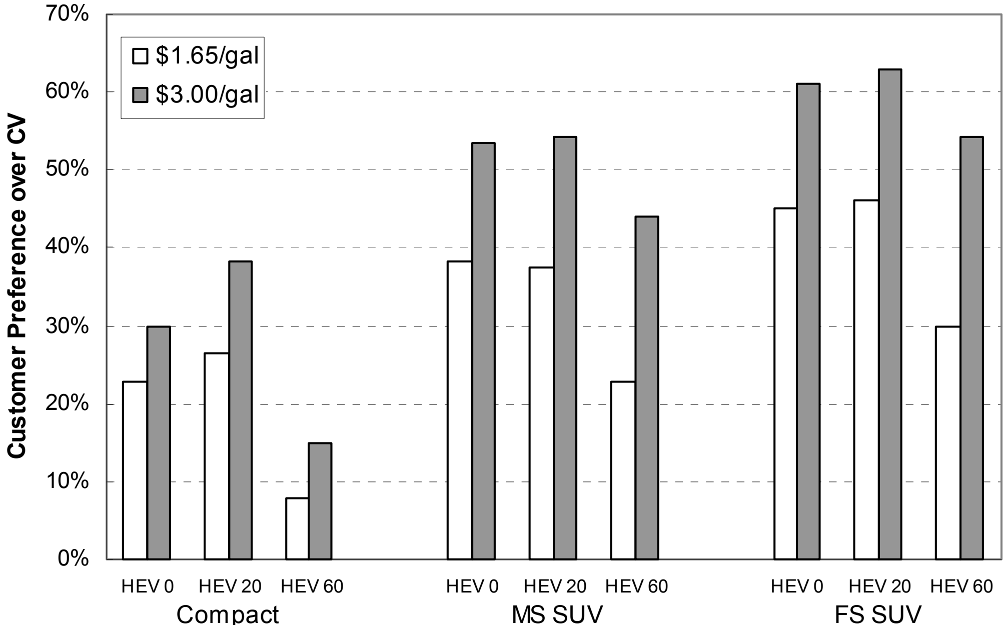

Figure 2-27
Market Preference versus Gasoline Price at the ANL Vehicle Price

2.7.3 Direct Assessment

About 100 direct assessment questions were asked in the quantitative computer-based interview discussed in Section 2.7.2. These direct assessment questions can be used to try to determine which HEV benefits consumers might value.

Table 2-8 shows the percentage of compact, SUV, and luxury car[15] respondents that indicated the HEV benefit listed would strongly influence them to purchase an HEV. Generally, HEV preferrers, a subset of the all-respondents group, value HEV benefits more than the percentages shown in Table 2-8 for the all-respondents group. (See Reference 1 for more details)

Another direct assessment question asked in the survey related to people's preference for plugging-in their vehicle at home versus going to a gasoline station. 52% of compact vehicle respondents, 51% of SUV respondents, and 46% of luxury car respondents strongly preferred plugging in at home to going to the gasoline station. Only about 7% of compact vehicle respondents, 6% of SUV respondents, and 7% of luxury car respondents strongly preferred going to the gasoline station.

---

[15] The luxury category included compact, SUV and mid-size vehicles in the luxury category. These were defined as vehicles with retail prices over $30,000. A full list of vehicle models in each category can be found in Reference 1.

Table 2-8
Customer Preference for HEV Benefits

HEV Benefit	Strong Influence on Purchase Decision		
	Compact	**SUV**	**Luxury**
Fuel cost savings	93%	88%	88%
Reducing maintenance (cost and personal time)	90%	87%	84%
50% longer range	78%	84%	72%
Leaving every morning with a fully-charged battery	75%	69%	65%
Better handling: balanced weight distribution	60%	65%	56%
Reducing air pollution and global warming gases	67%	62%	56%
Better handling: lower center of gravity	58%	65%	55%
Quietness (at stops and acceleration)	54%	54%	52%
Reducing dependence of foreign oil	62%	61%	53%
Less vibration and fatigue (at stops and acceleration)	57%	55%	54%

2.8 Conclusions

Among the many conclusions that have emerged from this study, the first publicly documented, systematic comparison of CVs and HEVs—including HEVs capable of being driven practical distances with battery power only—the following stand out:

- All HEVs, including plug-in hybrid engine-battery vehicles, can be designed for compact, mid-size SUV, and full-size SUV vehicle platform in ways that meet the performance and operating characteristics customers have come to expect and are familiar with.
- HEVs can offer major efficiency improvements as well as substantial reductions in the consumption of petroleum-based fuels and emissions of air pollution precursors (NO_x and HC) and carbon dioxide over gasoline CVs. All of these benefits increase with HEV electric range capability if that capability is fully utilized.
- Smog forming gases can be reduced by 10% for a compact HEV 0, 30% for a properly designed HEV 20, and 50% for a properly designed HEV 60. Similarly, in the mid-sized SUV category, an HEV 0 can reduce smog forming gases by 19%, an HEV 20 by 37%, and an HEV 60 by 54% when compared to a comparable CV. In the full-size SUV category, the HEV 0 reduces smog forming gases by 20%, the HEV 20 by 40%, and the HEV 60 by 55% when compared to a comparable CV[16].

---

[16] When compared to a SULEV conventional vehicle.

- Greenhouse (CO_2) emissions are reduced 20%, 40%, and 50%, respectively for a compact HEV 0, HEV 20, or HEV 60 replacing a compact CV. In the mid-size SUV, an HEV 0 reduces greenhouse gases by 31%, an HEV 20 by 46%, and an HEV 60 by 60% relative to a comparable CV. The full-size SUV shows a 30% reduction in greenhouse gases for the HEV 0, a 50% for the HEV 20, and a 60% for the HEV 60 relative to the comparable CV.
- Significant petroleum consumption reductions can be expected for properly designed HEVs. In the compact car, an HEV 0 can reduce petroleum consumption by 20%, an HEV 20 by 55%, and an HEV 60 by 80%. In the mid-size SUV, an HEV 0 can reduce petroleum consumption by 31%, an HEV 20 by 60%, and an HEV 60 by 85%. In the full-size SUV, petroleum consumption is reduced by 30% for an HEV 0, 60% for an HEV 20, and 85% for an HEV 60.
- All HEVs are estimated to cost more to produce than their CV equivalent. Estimated increases in the retail price equivalent (RPE) are from $2,500 to $3,600 for a compact HEV 0, from $4,500 to $6,000 for a compact HEV 20, and from $8,100 to $10,300 for a compact HEV 60. In the mid-size SUV, the RPE increase for an HEV 0 is from $4,000 to $5,500 higher, an HEV 20 from $6,400 to $8,500 higher, and an HEV 60 from $10,100 to $13,100 higher. The full-size SUV incremental RPE is from $4,500 to $6,300 for the HEV 0, $6,000 to $8,500 for the HEV 20, and $11,000 to $14,500 for the HEV 60. Battery costs are the primary reason for the incremental costs. The cost premium for compact HEVs will be higher by about $420 if future year conventional compact vehicles use more economical continuously variable transmissions (CVTs).
- Total energy (motor fuel and electricity) and maintenance costs of plug-in HEVs will be less than that for CVs, partially offsetting the impact of battery costs. The magnitude of the energy cost savings for HEVs depends on whether charging is done during off-peak periods with "time-of-use" meters. It also depends on whether electricity continues to be exempt from road tax. Incentives to buyers of HEVs could provide additional cost offsets, but more analysis is necessary to confidently quantify and compare life cycle costs.
- Under the vehicle design and cost assumptions used in the study, the Customer Preference Model indicates definite market potential for all HEVs, especially if the cost premium for HEV models can be minimized.
- The study indicates that people are willing to pay more for an HEV 60 than an HEV 20, more for an HEV 20 than an HEV 0, and more for an HEV 0 than a CV. While it is not clear why this is so, the study did indicate there are about 10 marketable HEV benefits that have a strong to high influence on the purchase decision.
- The majority of the people surveyed preferred plugging in a vehicle to fueling at the gas station**.**
- Some issues that have been identified need further examination to ensure successful commercialization, particularly battery cost and packaging.
- HEV 0 vehicles are in the early commercialization stage; the WG speculates that this is the result of decisions by the relevant manufacturers to subsidize this promising new automotive product. However, there is an unclear commercialization path for plug-in hybrid electric vehicles despite their substantial societal benefits because, in particular, there are no

corresponding automakers initiatives, presumably because of battery cost and battery replacement concerns. However, HEV 0s could be a stepping stone to plug-in hybrids.

- Because of the battery, the vehicle life assumption was limited to 100,000 miles and not 10 years of life. Real-world testing must be done regarding life.
- Significant uncertainty exists regarding HEV retail price. Each OEM is expected to price products differently. Many OEM prices consider not only costs and market demand, but proprietary considerations (e.g., the shifting of costs of one product onto other product lines), that the WG did not know how to quantify.
- In particular, incremental costs for all HEVs are significant in low and medium volume production (higher than the numbers in this report). Yet, there are also certain societal benefits if HEVs are commercialized. In addition, the infrastructure issues for HEVs are fewer compared with alternative fuel vehicles. (Even for plug-in HEVs, the survey found 86% had relatively easy access to a plug, with 120V systems being relatively hassle free).

3

REFERENCES

---

[1] Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options, EPRI, Palo Alto, CA, June 2001, Report # 1000349. Also available at http://www.epri.com/corporate/discover_epri/news/2001releases/010905_report1000349.pdf

[2] Brooker, A., et al, "ADVISOR 3.0 Documentation," user's guide available online at http://www.ctts.nrel.gov/analysis/advisor_doc, August 2000.

[3] Senger, R., M. Merkle, and J. Nelson, "Validation of ADVISOR as a Simulation Tool for a Series Hybrid Electric Vehicle," SAE paper 981133, 1998.

[4] Wipke, K, M. Cuddy and S. Burch, "ADVISOR 2.1: A User-Friendly Advanced Powertrain Simulation Using a Combined Backward/Forward Approach," NREL/JA-540-26839, September 1999

[5] Anderman, Menahem, Fritz Kalhammer, and Donald MacArthur, "Advanced Batteries for Electric Vehicles: An Assessment of Performance, Cost, and Availability," California Air Resources Board, June 2000

4

GLOSSARY

A	Ampere(s)
AC	Alternating current
ADVISOR	NREL's ADvanced VehIcle SimulatOR – a computer model that simulates conventional, hybrid electric and electric vehicle operation
AE	All-electric
AER	All-electric range, i.e., the nominal range of a plug-in HEV when operating in electric-only mode
AF	Alternative fuel
AFV	Alternative fuel vehicle
ANL	Argonne National Laboratory
APM	Accessory power module
ARB	California Air Resources Board
BACT	Best Available Control Technology
BPM	Brushless permanent magnet
CAFE	Corporate Average Fuel Economy
CBMM	Choice based market model
C_d	Coefficient of drag
CEC	California Energy Commission
CO_2	Carbon dioxide
CV	Conventional Vehicle

CVT	Continuously Variable Transmission
DC	Direct current
DOD	Depth of discharge
DOE	Department of Energy
EMI	Electromagnetic interference
EPAct	Energy Policy Act
EPRI	Electric Power Research Institute
EV	Electric vehicle
FCT	Full charge test. Simulates all-electric mode during ADVISOR modeling
FE	Fuel economy
FTP	Federal test procedure. A combination of FUDS and HWFET cycles
FUDS	Federal Urban Driving Cycle. Used to determine fuel economy and emissions for city driving.
GFCI	Ground fault circuit interrupt
g/kWh	Grams per kilowatt hour
g/mi	Grams per mile
GREET	ANL's Greenhouse Gas Emission Model
HEV	Hybrid Electric Vehicle
HEV 0	A parallel hybrid with no all-electric range
HEV 20	A parallel hybrid with "plug-in" capability (that is, capability for battery recharging from an off-board source of electricity) and a battery providing about 20 miles of all-electric range
HEV 60	A parallel hybrid with plug-in capability and a larger battery providing about 60 miles of all-electric range
HVAC	Heating, ventilating, and air conditioning

HWFET	Highway Fuel Economy Test. Used in determining fuel economy during highway driving
ICE	Internal combustion engine
IGBT	Insulated-gate bipolar transistor
ILEV	Inherently low emission vehicle
kg	Kilograms
kW	Kilowatt(s)
kWh	Kilowatt hour(s)
kWh/mi	Kilowatt hours per mile
mg/mi	Milligrams per mile
mpeg	Miles per equivalent gasoline gallon. Miles per kilowatt hour are converted to mpeg using 33.44 kWh/gasoline gallon
mpg	Miles per gasoline gallon
mph	Miles per hour
MWP	Mileage weighted probability
MSRP	Manufacturer suggested retail price
NiMH	Nickel metal hydride
NMOG	Non-methane organic gases
NO_x	Oxides of nitrogen
NPTS	Nationwide Personal Transportation Survey
NREL	National Renewable Energy Laboratory
OEM	Original Equipment Manufacturer
OVC	Off-vehicle charging
PCT	Partial charge test. Simulates charge sustaining mode during ADVISOR modeling
PNGV	Partnership for a New Generation of Vehicles

PWM	Pulse width modulation
PZEV	Partial ZEV
ROG	Reactive organic gases
RPE	Retail price equivalent
SAE	Society of Automotive Engineers
SC03	A driving cycle that captures air conditioning load effects and is part of the supplemental federal test procedure
SCAQMD	South Coast Air Quality Management District
SFTP	Supplemental Federal Test Procedure. A combination of FUDS, HWFET, US06, and SC03 driving cycles.
SOC	State of charge
SULEV	Super ultra low emission vehicle
SUV	Sports Utility Vehicle
UF	Utility Factor
ULEV	Ultra Low Emission Vehicle
US06	A driving cycle that captures high speed and aggressive driving and is part of the supplemental federal test procedure
V	Volt(s)
W	Watt(s)
WG	Hybrid Electric Vehicle Working Group
Wh	Watt-hour(s)
ZEV	Zero Emission Vehicle

A

SUMMARY AND CONCLUSIONS

The following tables support the tables and charts Section 2 of the report. Table A-1 lists the design parameters used in the ADVISOR modeling runs. Table A-2 gives the performance targets for the three platforms. Tables A-3 through A-5 present the ADVISOR output for each of the three platforms. Tables A-6 through A-8 show the breakdown of vehicle mass for the various vehicle designs and platforms. Tables A-9 through A-11 represent fuel-cycle calculations of emissions and energy use. Tables A-12 through A-14 show the conventional vehicle MSRP for each of the three platforms. Tables A-15 through A-17 show the average of the ANL and Base Method fully loaded component costs. Table A-18 shows the Base and ANL method RPEs. Table A-19 presents battery module costs versus battery power to energy ratio. Tables A-20 through A-22 show calculations of fuel costs. Tables A-23 through A-25 show calculations of maintenance costs. Finally, market preference versus various vehicle price scenarios is given in Tables A-26 through A-28.

Table A-1
Design Parameters

Parameter	Compact Car	Mid-Size SUV	Full-Size SUV
Drag coefficient	0.315	0.410	0.441
Frontal area	1.974 m^2	2.840 m^2	3.013 m^2
Coefficient of rolling resistance	0.008	0.006	0.006
Cargo mass	136 kg	136 kg	136 kg
Glider mass	743 kg	1,575 kg	1,876 kg
Wheel rolling radius	0.282 m	0.368 m	0.368 m
Average electrical accessory load	400 W	600 W	700 W
Average electrical system efficiency	85%	85 %	85%
Average air conditioner load[a]	1,000 W	2,500 W	3,000 W

[a] Used in SC03 cycle only

Table A-2
Performance Targets (Worst Case for HEV 20 and HEV 60[17])

Performance Target	Compact Car	Mid-Size SUV	Full-Size SUV
0 to 60 mph acceleration[a]	11.7 seconds	9.2 seconds	8.5 seconds
50 to 70 mph acceleration[b]	6.9 seconds	5.4 seconds	4.8 seconds
Minimum sustained top speed	90 mph		
Gradeability at 50 mph for 15 minutes[a,c]	7.2%		
Gradeability at 30 mph for 30 minutes[a,c]	7.2%		
Minimum towing capability[d]	450 kg	2,270 kg	3,175 kg
ZEV range on FUDS/HWFET cycle[e]	20 miles for HEV 20, 60 miles for HEV 60		
Minimum total range on FUDS cycle	344 miles	347 miles	435 miles
US06 capability from any condition	2 cycles	Continuous	Continuous
Engine starts/stopsf	Less than 30		
HEV 20 & HEV 60 engine turn-on speed	Above 60 mph only unless at or below 21% SOC		

[a] Initial SOC = 20.5% for HEV 20 and HEV 60, 60% for HEV 0.

[b] Running start (derived from 0 to 70 mph acceleration run).

[c] Initial SOC = charge sustaining SOC, final SOC $\geq$ 20%.

[d] At 55 mph on 0% grade.

[e] Must provide ZEV range that HEV was designed for (i.e. HEV 20 must provide 20 miles ZEV range on FUDS/HWFET cycle).

[f] A greater number of engine start/stop cycles allows an HEV to achieve greater fuel economy. However, there may be a concern over driveability. The number of on/off cycles was checked on the FUDS driving cycles. See Reference 1 for more information.

---

[17] The constraints were enforced at low SOC for the grid-connected HEVs (see table footnotes).

Table A-3
Compact Car Modeling Results

Parameter	Units	CV	HEV 0	HEV 20	HEV 60
Component Sizes					
Engine	kW	74	53	41	32
Motor	kW	—	23.3	37.3	60.7
Energy Storage System	modules	—	13	26	26
Energy Storage System	kW(rated)	—	24.0	39.6	85.8
Energy Storage System	kWh(rated)	—	2.20	5.08	15.45
Vehicle mass	kg	1209	1221	1295	1381
All-electric range					
FUDS	mi	—	—	22.0	61.2
HWFET	mi			22.0	62.1
Modeled Fuel Economy					
PCT Urban	mpg	31.6	48.5	49.0	51.3
Final SOC City	—	—	0.357	0.210	0.209
PCT Hwy	mpg	49.3	50.5	58.0	60.4
Final SOC Hwy	—	—	0.606	0.218	0.215
FCT Urban	mpeg	—	—	142.2	142.4
UF Urban	—	—	—	0.34	0.64
UFW Urban	mpeg	—	—	63.1	86.9
FCT Hwy	mpg	—	—	142.2	144.5
UF Hwy	—	—	—	0.34	0.64
UFW Hwy	mpg	—	—	72.6	96.3
SAE J1711 Fuel Economy					
Weighted Urban	mpeg	31.6	48.5	55.1	64.5
Weighted Hwy	mpeg	49.3	50.5	64.5	74.2
Composite	mpeg	37.7	49.4	59.0	68.5
Utility Factor Weighted	mpeg	37.7	49.4	67.0	90.9
Gasoline Urban	mpg	31.6	48.5	49.0	51.3
Gasoline Highway	mpg	49.3	50.5	58.0	60.4
Gasoline Composite	mpg	37.7	49.4	52.7	55.0
Electric, Urban	kWh/mi	—	—	0.249	0.249
Electric, Highway	kWh/mi	—	—	0.249	0.245
Electric Composite	mpeg			134.1	135.1
Average UF				0.340	0.640
Acceleration Times (s)	0-30	3.4	3.6	3.5	3.0
	0-60	10.7	10.5	10.7	8.7
	40-60	4.8	5.1	5.3	4.2
	50-70	6.9	6.2	6.8	5.1
Top Speed, mph		124	101	113	98

Table A-4
Mid-Size SUV Modeling Results

Parameter	Units	CV	HEV 0	HEV 20	HEV 60
Component Sizes					
Engine	kW	156	115	95	72
Motor	kW	—	51.3	84.0	88.7
Energy Storage System	modules	—	25	27.5	24.5
Energy Storage System	kW(rated)	—	55.6	77.2	142.9
Energy Storage System	kWh(rated)	—	4.12	7.85	23.37
Vehicle mass	kg	2256	2333	2402	2546
All-electric range					
FUDS	mi	—	—	20.5	60.8
HWFET	mi			20.6	61.2
Modeled Fuel Economy					
PCT Urban	mpg	18.4	30.6	32.4	33.5
Final SOC City	—	—	0.655	0.203	0.203
PCT Hwy	mpg	29.7	36.5	37.9	38.8
Final SOC Hwy	—	—	0.660	0.210	0.202
FCT Urban	mpeg	—	—	96.3	101.2
UF Urban	—	—	—	0.32	0.63
UFW Urban	mpeg	—	—	41.0	58.0
FCT Hwy	mpg	—	—	95.7	101.4
UF Hwy	—	—	—	0.32	0.64
UFW Hwy	mpg	—	—	47.0	63.9
SAE J1711 Fuel Economy					
Weighted Urban	mpeg	18.4	30.6	36.2	42.2
Weighted Hwy	mpeg	29.7	36.5	42.0	48.6
Composite	mpeg	22.2	33.0	38.6	44.5
Utility Factor Weighted	mpeg	22.2	33.0	43.5	60.8
Gasoline Urban	mpg	18.4	30.6	32.4	33.2
Gasoline Highway	mpg	29.7	36.5	37.9	39.0
Gasoline Composite	mpg	22.2	33.0	34.7	35.6
Electric, Urban	kWh/mi	—	—	0.368	0.350
Electric, Highway	kWh/mi	—	—	0.371	0.350
Electric Composite	mpeg			90.5	95.5
Average UF				0.318	0.634
Acceleration Times (s)	0-30	3.4	3.9	3.7	3.5
	0-60	9.2	9.3	9.2	9.3
	40-60	4.1	3.9	4.0	4.1
	50-70	5.4	5.0	5.1	5.2
Top Speed, mph		121	100	110	95

Table A-5
Full-Size SUV Modeling Results

Parameter	Units	CV	HEV 0	HEV 20	HEV 60
Component Sizes					
Engine	kW	212	145	115	90
Motor	kW	—	65.3	98.0	116.7
Energy Storage System	modules	—	24	26	28
Energy Storage System	kW(rated)	—	87.2	115.0	163.3
Energy Storage System	kWh(rated)	—	5.19	9.29	27.67
Vehicle mass	kg	2757	2765	2824	2982
All-electric range					
FUDS	mi	—	—	20.8	61.6
HWFET	mi			20.6	62.0
Modeled Fuel Economy					
PCT Urban	mpg	14.9	25.6	27.6	28.5
Final SOC City	—	—	0.650	0.203	0.209
PCT Hwy	mpg	24.8	30.5	32.2	32.7
Final SOC Hwy	—	—	0.660	0.207	0.215
FCT Urban	mpeg	—	—	82.7	86.2
UF Urban	—	—	—	0.32	0.64
UFW Urban	mpeg	—	—	35.2	49.9
FCT Hwy	mpg	—	—	81.0	86.1
UF Hwy	—	—	—	0.32	0.64
UFW Hwy	mpg	—	—	39.9	54.3
SAE J1711 Fuel Economy					
Weighted Urban	mpeg	14.9	25.6	30.9	36.3
Weighted Hwy	mpeg	24.8	30.5	35.6	40.8
Composite	mpeg	18.2	27.6	32.9	37.9
Utility Factor Weighted	mpeg	18.2	27.6	37.1	51.8
Gasoline Urban	mpg	14.9	25.6	27.6	28.5
Gasoline Highway	mpg	24.8	30.5	32.2	32.7
Gasoline Composite	mpg	18.2	27.6	29.5	30.2
Electric, Urban	kWh/mi	—	—	0.429	0.412
Electric, Highway	kWh/mi	—	—	0.438	0.412
Electric Composite	mpeg			77.2	81.2
Average UF				0.322	0.640
Acceleration Times (s)	0-30	3.3	3.8	3.4	3.3
	0-60	8.5	8.8	8.8	8.7
	40-60	3.7	3.6	3.8	3.9
	50-70	4.8	4.6	4.9	4.9
Top Speed, mph		131	111	109	96

Table A-6
Component Mass and Total Mass Results for Compact Cars

Component	Mass (kg)			
	CV	**HEV 0**	**HEV 20**	**HEV 60**
Engine	103.7	73.0	56.0	43.6
Engine Thermal	5.0	4.6	2.6	2.4
Lube	5.0	4.0	3.0	3.0
Engine Misc.	22.0	7.0	7.0	7.0
Engine Mounts	4.0	4.0	4.0	4.0
Engine Total	**139.7**	**92.6**	**72.6**	**60.0**
Exhaust/Evap System	**20.0**	**12.0**	**10.0**	**7.0**
Transmission	**80.0**	**40.0**	**40.0**	**40.0**
Generator/Alternator	4.7	—	—	—
A/C Compressor	6.2	11.2	13.0	15.0
A/C Condenser	2.2	2.3	2.6	3.2
A/C Misc.	12.6	12.6	12.6	12.6
Accessory Power Module	—	10.0	10.0	10.0
Accessory Power Total	**25.6**	**36.1**	**38.2**	**40.8**
Starter Motor	5.0			
Electric Motor		12.0	19.0	32.0
Power Inverter		5.0	5.0	5.0
Motor/Electronics Thermal		16.6	16.6	16.6
Electric Traction Total	**5.0**	**33.6**	**40.6**	**53.6**
Fuel Storage (tank + lines)	10.0	6.4	6.0	5.6
Accessory Battery	14.8	5.0	5.0	5.0
Energy Batteries		57.0	137.0	218.0
Pack Tray		7.0	9.0	15.0
Pack Hardware		13.5	13.5	13.5
Battery Thermal		12.5	12.5	12.5
Energy Storage Total	**24.8**	**101.3**	**183.0**	**269.6**
Charge Port			7.0	7.0
Charging Total	**0.0**	**0.0**	**7.0**	**7.0**
Total Power Train	**295**	**316**	**391**	**478**
Glider (including power steering)	743	743	743	743
Mass of fuel for full tank	34.3	26.5	24.8	23.7
Total Curb Mass	**1073**	**1085**	**1159**	**1245**
Driver and cargo mass	136	136	136	136
Total Test Mass	**1209**	**1221**	**1295**	**1381**

Table A-7
Component Mass and Total Mass Results for Mid-size SUVs

Component	Mass (kg)			
	CV	HEV 0	HEV 20	HEV 60
Engine	212.0	149.5	123.5	93.6
Engine Thermal	11.0	7.2	6.0	4.5
Lube	4.4	4.4	4.0	3.5
Engine Misc.	14.0	14.0	14.0	14.0
Engine Mounts	4.0	4.0	4.0	4.0
Engine Total	**245.4**	**179.1**	**151.5**	**119.6**
Exhaust/Evap System	**38.5**	**38.1**	**33.2**	**27.6**
Transmission	**87.3**	**55.0**	**60.0**	**65.0**
Transfer Case w/ Prop Shafts	**50.8**	**50.8**	**50.8**	**50.8**
Generator/Alternator	6.3	—	—	—
A/C Compressor	6.1	12.0	14.0	16.0
A/C Condenser	3.4	5.0	7.0	9.0
A/C Misc.	3.4	12.6	12.6	12.6
Accessory Power Module	—	11.0	11.0	11.0
Accessory Power Total	**19.3**	**40.6**	**44.6**	**48.6**
Starter Motor	3.5			
Electric Motor		27.3	37.3	47.2
Power Inverter		6.0	6.0	6.0
Motor/Electronics Thermal		18.0	18.0	18.0
Electric Traction Total	**3.5**	**51.3**	**61.3**	**71.2**
Fuel Storage (tank + lines)	20.1	15.0	12.0	9.0
Accessory Battery	20.8	5.0	5.0	5.0
Energy Batteries		107.6	184.8	340.9
Pack Tray		9.0	12.0	23.0
Pack Hardware		13.5	13.5	13.5
Battery Thermal		16.6	16.6	16.6
Energy Storage Total	**40.9**	**166.7**	**243.9**	**408.0**
Charge Port			7.0	7.0
Charging Total	**0.0**	**0.0**	**7.0**	**7.0**
Total Power Train	486	582	652	798
Glider (including power steering)	1575	1575	1575	1575
Mass of fuel for full tank	59.5	40.5	38.5	37.5
Total Curb Mass	**2120**	**2197**	**2266**	**2390**
Driver and cargo mass	136	136	136	136
Total Test Mass	**2256**	**2333**	**2402**	**2546**

Table A-8
Component Mass and Total Mass Results for Full-size SUVs

Component	Mass (kg)			
	CV	**HEV 0**	**HEV 20**	**HEV 60**
Engine	275.6	188.5	149.5	117.0
Engine Thermal	13.4	9.1	7.2	5.7
Lube	7.8	5.0	5.0	5.0
Engine Misc.	38.0	14.0	14.0	14.0
Engine Mounts	8.5	4.0	4.0	4.0
Engine Total	**343.3**	**220.6**	**179.7**	**145.7**
Exhaust/Evap System	**61.7**	**45.4**	**38.1**	**32.0**
Transmission	**115.0**	**65.0**	**70.0**	**75.0**
Transfer Case w/ Prop Shafts	**55.8**	**55.8**	**55.8**	**55.8**
Generator/Alternator	6.0	—	—	—
A/C Compressor	10.0	13.0	15.0	17.0
A/C Condenser	4.0	5.0	7.0	9.0
A/C Misc.	12.6	12.6	12.6	12.6
Accessory Power Module	—	12.0	12.0	12.0
Accessory Power Total	**32.6**	**42.6**	**46.6**	**50.6**
Starter Motor	8.0			
Electric Motor		34.8	52.3	62.1
Power Inverter		7.0	7.0	7.0
Motor/Electronics Thermal		20.0	20.0	20.0
Electric Traction Total	**8.0**	**61.8**	**79.3**	**89.1**
Fuel Storage (tank + lines)	20.0	15.0	12.0	9.0
Accessory Battery	16.8	5.0	5.0	5.0
Energy Batteries		140.9	218.4	389.7
Pack Tray		10.0	13.0	25.0
Pack Hardware		13.5	13.5	13.5
Battery Thermal		16.6	16.6	16.6
Energy Storage Total	**36.8**	**201.0**	**278.5**	**458.8**
Charge Port			7.0	7.0
Charging Total	**0.0**	**0.0**	**7.0**	**7.0**
Total Power Train	**653**	**692**	**755**	**914**
Glider (including power steering)	1876	1876	1876	1876
Mass of fuel for full tank	92.1	61.3	57.4	56.0
Total Curb Mass	**2621**	**2629**	**2688**	**2846**
Driver and cargo mass	136	136	136	136
Total Test Mass	**2757**	**2765**	**2824**	**2982**

Table A-9
Fuel-cycle Energy and Emission Results for Compact Car for the Average Driving Schedule and Charging Nightly

Parameter	CV	HEV 0	HEV 20	HEV 60
Annual City Electric Miles			2,585	4,959
Annual Hwy Electric Miles			2,691	5,161
Annual City Gasoline Miles	6,528	6,528	3,943	1,569
Annual Hwy Gasoline Miles	6,794	6,794	4,103	1,633
Adjusted[a] City Electric FE, kWh/mi	—	—	0.277	0.277
Adjusted Hwy Electric FE, kWh/mi	—	—	0.320	0.315
Adjusted City Gasoline FE, mpg	28.44	43.66	44.11	46.16
Adjusted Hwy Gasoline FE, mpg	38.45	39.38	45.22	47.11
Annual Gallons of Gasoline Used	406	322	180	69
Annual kWh of Electricity Used	—	—	1,577	2,997
Annual Fuel-cycle CO_2, kg	833	660	1,043	1,420
Annual Vehicle CO_2, kg	3,453	2,738	1,531	584
Annual Total CO_2, kg	4,286	3,398	2,574	2,004
Annual Fuel-cycle HC, grams	515	408	256	139
Annual Tailpipe HC, grams	97	97	59	23
Annual Evaporative HC, grams	187	187	187	187
Annual Total HC, grams	799	692	501	349
Annual Fuel-cycle NO_x, grams	60	48	108	164
Annual Tailpipe NO_x, grams	333	333	201	80
Annual Total NO_x, grams	393	381	309	244
Annual Total Smog[b], grams	1,192	1,073	810	594
% CO_2 Reduction from CV	0%	21%	40%	53%
% Smog Reduction from CV	0%	10%	32%	50%
% Petroleum Reduction from CV	0%	21%	56%	83%
CO_2 Fuel-cycle g/mi	63	50	78	107
CO_2 Vehicle g/mi	259	205	115	44
HC g/mi	0.060	0.052	0.038	0.026
NOx g/mi	0.030	0.029	0.023	0.018
Fuel-cycle Petroleum Energy, kWh/mi	1.284	1.018	0.569	0.217
Fuel-cycle Nat Gas Energy, kWh/mi	0.049	0.039	0.306	0.548

[a] Adjusted fuel economies use EPA labeling discounts (10% city, 22% highway).

[b] Smog is smog precursors (HC plus NO_x)

Table A-10
Fuel-cycle Energy and Emission Results for Mid-Size SUV for the Average Driving Schedule and Charging Nightly

Parameter	CV	HEV 0	HEV 20	HEV 60
Annual City Electric Miles			2,585	4,959
Annual Hwy Electric Miles			2,691	5,161
Annual City Gasoline Miles	6,528	6,528	3,943	1,569
Annual Hwy Gasoline Miles	6,794	6,794	4,103	1,633
Adjusted[a] City Electric FE, kWh/mi	—	—	0.406	0.384
Adjusted Hwy Electric FE, kWh/mi	—	—	0.466	0.441
Adjusted City Gasoline FE, mpg	16.56	27.54	29.16	30.15
Adjusted Hwy Gasoline FE, mpg	23.17	28.47	29.56	30.26
Annual Gallons of Gasoline Used	687	476	274	106
Annual kWh of Electricity Used	—	—	2,336	4,247
Annual Fuel-cycle CO_2, kg	1,409	975	1,559	2,031
Annual Vehicle CO_2, kg	5,844	4,043	2,329	901
Annual Total CO_2, kg	7,253	5,018	3,888	2,932
Annual Fuel-cycle HC, grams	871	602	388	208
Annual Tailpipe HC, grams	97	97	59	23
Annual Evaporative HC, grams	187	187	187	187
Annual Total HC, grams	1,155	887	633	418
Annual Fuel-cycle NO_x, grams	102	71	161	234
Annual Tailpipe NO_x, grams	333	333	201	80
Annual Total NO_x, grams	435	404	362	314
Annual Total Smog[b], grams	1,590	1,290	995	732
% CO_2 Reduction from CV	0%	31%	46%	60%
% Smog Reduction from CV	0%	19%	37%	54%
% Petroleum Reduction from CV	0%	31%	60%	85%
CO_2 Fuel-cycle g/mi	106	73	117	152
CO_2 Vehicle g/mi	439	304	175	68
HC g/mi	0.087	0.067	0.048	0.031
NOx g/mi	0.033	0.030	0.027	0.024
Fuel-cycle Petroleum Energy, kWh/mi	2.173	1.503	0.866	0.335
Fuel-cycle Nat Gas Energy, kWh/mi	0.083	0.058	0.454	0.778

[a] Adjusted fuel economies use EPA labeling discounts (10% city, 22% highway).

[b] Smog is smog precursors (HC plus NO_x)

Table A-11
Fuel-cycle Energy and Emission Results for Full-Size SUV for the Average Driving Schedule and Charging Nightly

Parameter	CV	HEV 0	HEV 20	HEV 60
Annual City Electric Miles			2,585	4,959
Annual Hwy Electric Miles			2,691	5,161
Annual City Gasoline Miles	6,528	6,528	3,943	1,569
Annual Hwy Gasoline Miles	6,794	6,794	4,103	1,633
Adjusted[a] City Electric FE, kWh/mi	—	—	0.477	0.457
Adjusted Hwy Electric FE, kWh/mi	—	—	0.561	0.528
Adjusted City Gasoline FE, mpg	13.41	23.04	24.84	25.65
Adjusted Hwy Gasoline FE, mpg	19.34	23.79	25.12	25.51
Annual Gallons of Gasoline Used	838	569	322	125
Annual kWh of Electricity Used	—	—	2,742	4,995
Annual Fuel-cycle CO_2, kg	1,718	1,166	1,831	2,390
Annual Vehicle CO_2, kg	7,123	4,836	2,738	1,064
Annual Total CO_2, kg	8,841	6,002	4,569	3,454
Annual Fuel-cycle HC, grams	1,062	721	456	246
Annual Tailpipe HC, grams	97	97	59	23
Annual Evaporative HC, grams	187	187	187	187
Annual Total HC, grams	1,346	1,005	701	456
Annual Fuel-cycle NO_x, grams	125	85	189	275
Annual Tailpipe NO_x, grams	333	333	201	80
Annual Total NO_x, grams	458	418	390	355
Annual Total Smog[b], grams	1,804	1,422	1,091	811
% CO_2 Reduction from CV	0%	32%	48%	61%
% Smog Reduction from CV	0%	21%	39%	55%
% Petroleum Reduction from CV	0%	32%	62%	85%
CO_2 Fuel-cycle g/mi	129	88	137	179
CO_2 Vehicle g/mi	535	363	206	80
HC g/mi	0.101	0.075	0.053	0.034
NOx g/mi	0.034	0.031	0.029	0.027
Fuel-cycle Petroleum Energy, kWh/mi	2.649	1.798	1.018	0.396
Fuel-cycle Nat Gas Energy, kWh/mi	0.101	0.069	0.533	0.915

[a] Adjusted fuel economies use EPA labeling discounts (10% city, 22% highway).

[b] Smog is smog precursors (HC plus NO_x)

Table A-12
Conventional Compact Car Retail Price

Saturn 2001 SL1	
ZZH69 Sedan 4D (Auto)	$12,490
Destination Charge	$465
Air Conditioning	$960
Total MSRP	$13,915

http:\\www.kbb.com

Table A-13
Conventional Mid-Size SUV Retail Price

Ford 2001 Explorer 4WD	
U73 XLT Utility 4D	$29,975
Destination Charge	$600
Trailer Towing Package	$355
Total MSRP	$30,930

http:\\www.kbb.com

Table A-14
Conventional Full-Size SUV Retail Price

Chevrolet 2001 Suburban 1500 4WD	
CK 15906 Wagon 4D	$28,837
Destination Charge	$765
LS Package	$7,423
Trailer Towing Package	$285
Liftgate/Liftglass	$250
Total MSRP	$37,560

http:\\www.kbb.com

Table A-15
Compact Car Component Retail Price Equivalent Average for Base and ANL Methods

Component	CV	HEV 0	HEV 20	HEV 60
Glider[a]	$9,209	$9,287	$9,287	$9,287
Engine + Exhaust	$2,791	$2,331	$1,962	$1,756
Transmission	$1,520	$978	$978	$978
Accessory Power	$329	$468	$468	$468
Electric Traction	$57	$1,546	$2,041	$2,867
Energy Storage System	$56	$2,399	$3,739	$7,036
On Vehicle Charging System	—	—	$760	$760
Total Average Vehicle RPE	$13,962	$17,008	$19,235	$23,153

[a] Development costs on glider less for CV in Base Method.

Table A-16
Mid-Size SUV Component Retail Price Equivalent Average for Base and ANL Methods

Component	CV	HEV 0	HEV 20	HEV 60
Glider[a]	$22,969	$23,047	$23,047	$23,047
Engine + Exhaust	$5,132	$4,298	$3,788	$2,953
Transmission	$2,269	$1,540	$1,540	$1,540
Accessory Power	$457	$609	$609	$609
Electric Traction	$95	$2,535	$3,690	$3,856
Energy Storage System	$56	$3,679	$4,986	$9,702
On Vehicle Charging System	—	—	$746	$860
Total Average Vehicle RPE	$30,977	$35,708	$38,406	$42,566

[a] Development costs on glider less for CV in Base Method.

Table A-17
Full-Size SUV Component Retail Price Equivalent Average for Base and ANL Methods

Component	CV	HEV 0	HEV 20	HEV 60
Glider[a]	$27,699	$27,777	$27,777	$27,777
Engine + Exhaust	$7,032	$5,644	$4,205	$,3,684
Transmission	$2,269	$1,540	$1,540	$1,540
Accessory Power	$457	$609	$609	$609
Electric Traction	$95	$3,030	$4,185	$4,845
Energy Storage System	$56	$4,390	$5,811	$11,035
On Vehicle Charging System	—	—	$760	$874
Total Average Vehicle RPE	$37,607	$42,989	$44,886	$50,363

[a] Development costs on glider less for CV in Base Method.

Table A-18
Vehicle RPEs for Base and ANL Methods

Vehicle Type	Compact Car		Mid-Size SUV		Full-Size SUV	
	Base	ANL	Base	ANL	Base	ANL
CV	$14,009	$13,915	$31,024	$30,930	$37,654	$37,560
HEV 0	$17,611	$16,405	$36,527	$34,890	$43,936	$42,042
HEV 20	$20,071	$18,398	$39,529	$37,311	$46,196	$43,577
HEV 60	$24,314	$21,992	$44,122	$41,039	$52,159	$48,566

Table A-19
NiMH Battery Module Costs to OEM

Vehicle Type	Power (rated) kW	Energy (rated) kWh	Power / Energy W/Wh	Secific Cost $/kWh
Compact Car				
HEV 0	24.0	2.20	10.9	$335
HEV 20	39.6	5.08	7.8	$300
HEV 60	85.8	15.45	5.6	$274
Mid-Size SUV				
HEV 0	55.6	4.12	13.5	$364
HEV 20	77.2	7.85	9.8	$323
HEV 60	142.9	23.37	6.1	$280
Full-Size SUV				
HEV 0	87.2	5.19	16.8	$402
HEV 20	115.0	9.29	12.4	$352
HEV 60	163.3	27.67	5.9	$278

Table A-20
Fuel Costs per Mile for Compact Car for the Average Driving Schedule and Charging Nightly

Parameter	CV	HEV 0	HEV 20	HEV 60
Annual City Electric Miles			2,585	4,959
Annual Hwy Electric Miles			2,691	5,161
Annual City Gasoline Miles	6,528	6,528	3,943	1,569
Annual Hwy Gasoline Miles	6,794	6,794	4,103	1,633
Adjusted[a] City Electric FE, kWh/mi	—	—	0.277	0.277
Adjusted Hwy Electric FE, kWh/mi	—	—	0.320	0.315
Adjusted City Gasoline FE, mpg	28.44	43.66	44.11	46.16
Adjusted Hwy Gasoline FE, mpg	38.45	39.38	45.22	47.11
Annual Gallons of Gasoline Used	406	322	180	69
Annual kWh of Electricity Used	—	—	1,577	2,997
Gasoline Costs[b], $/gallon	$1.65	$1.65	$1.65	$1.65
Electricity Costs[c], $/kWh	$0.06	$0.06	$0.06	$0.06
Annual Gasoline Costs	$670	$531	$297	$113
Annual Electricity Costs	—	—	$95	$180
Annual Fuel Costs	$670	$531	$392	$293
Gasoline cost per mile	5.03¢	3.99¢	2.23¢	0.85¢
Electricity cost per mile	—	—	0.71¢	1.35¢
Total fuel costs per mile	5.03¢	3.99¢	2.94¢	2.20¢

[a] Adjusted fuel economies use EPA labeling discounts (10% city, 22% highway).

[b] Estimated national average gasoline price at time of report

[c] 5 city average off-peak electricity prices for charging EVs (Boston, Atlanta, Los Angeles, Phoenix, San Francisco).

Table A-21
Fuel Costs per Mile for Mid-Size SUV for the Average Driving Schedule and Charging Nightly

Parameter	CV	HEV 0	HEV 20	HEV 60
Annual City Electric Miles			2,585	4,959
Annual Hwy Electric Miles			2,691	5,161
Annual City Gasoline Miles	6,528	6,528	3,943	1,569
Annual Hwy Gasoline Miles	6,794	6,794	4,103	1,633
Adjusted[a] City Electric FE, kWh/mi	—	—	0.406	0.384
Adjusted Hwy Electric FE, kWh/mi	—	—	0.466	0.441
Adjusted City Gasoline FE, mpg	16.56	27.54	29.16	30.15
Adjusted Hwy Gasoline FE, mpg	23.17	28.47	29.56	30.26
Annual Gallons of Gasoline Used	687	476	274	106
Annual kWh of Electricity Used	—	—	2,336	4,247
Gasoline Costs[b], $/gallon	$1.65	$1.65	$1.65	$1.65
Electricity Costs[c], $/kWh	$0.06	$0.06	$0.06	$0.06
Annual Gasoline Costs	$1,134	$785	$452	$175
Annual Electricity Costs	—	—	$140	$255
Annual Fuel Costs	$1,134	$785	$592	$430
Gasoline cost per mile	8.52¢	5.89¢	3.39¢	1.31¢
Electricity cost per mile	—	—	1.05¢	1.91¢
Total fuel costs per mile	8.52¢	5.89¢	4.44¢	3.22¢

[a] Adjusted fuel economies use EPA labeling discounts (10% city, 22% highway).

[b] Estimated national average gasoline price at time of report

[c] 5 city average off-peak electricity prices for charging EVs (Boston, Atlanta, Los Angeles, Phoenix, San Francisco).

Table A-22
Fuel Costs per Mile for Full-Size SUV for the Average Driving Schedule and Charging Nightly

Parameter	CV	HEV 0	HEV 20	HEV 60
Annual City Electric Miles			2,585	4,959
Annual Hwy Electric Miles			2,691	5,161
Annual City Gasoline Miles	6,528	6,528	3.943	1,569
Annual Hwy Gasoline Miles	6,794	6,794	4,103	1,633
Adjusted[a] City Electric FE, kWh/mi	—	—	0.477	0.457
Adjusted Hwy Electric FE, kWh/mi	—	—	0.561	0.528
Adjusted City Gasoline FE, mpg	13.41	23.04	24.84	25.65
Adjusted Hwy Gasoline FE, mpg	19.34	23.79	25.12	25.51
Annual Gallons of Gasoline Used	838	569	322	125
Annual kWh of Electricity Used	—	—	2,742	4,995
Gasoline Costs[b], $/gallon	$1.65	$1.65	$1.65	$1.65
Electricity Costs[c], $/kWh	$0.06	$0.06	$0.06	$0.06
Annual Gasoline Costs	$1,383	$939	$531	$207
Annual Electricity Costs	—	—	$165	$300
Annual Fuel Costs	$1,383	$939	$696	$507
Gasoline cost per mile	10.38¢	7.05¢	3.99¢	1.55¢
Electricity cost per mile	—	—	1.24¢	2.25¢
Total fuel costs per mile	10.38¢	7.05¢	5.23¢	3.80¢

[a] Adjusted fuel economies use EPA labeling discounts (10% city, 22% highway).

[b] Estimated national average gasoline price at time of report

[c] 5 city average off-peak electricity prices for charging EVs (Boston, Atlanta, Los Angeles, Phoenix, San Francisco).

Table A-23
Scheduled Maintenance Costs for Compact Car using Average Driving Schedule and Nightly Charging[a]

Vehicle Type	CV	HEV 0	HEV 20	HEV 60
Engine Type	I-4	I-4	I-3	I-3
Number of Lifetime Oil Changes	16	16	10	7
Oil and Filter Costs per Oil Change	$23	$23	$20	$20
Oil Change Labor per Oil Change	$21	$21	$21	$21
Interval between Oil Changes, years	0.45	0.45	0.75	1.00
Lifetime Oil Change Cost	$696	$696	$410	$287
Number of Lifetime Air Filter Replacements	3	3	2	0
Air Filter Costs per Replacement	$20	$20	$15	$15
Air Filter Replacement Labor per Replacement	$6	$6	$6	$6
Interval Between Replacements, years	2.25	2.25	3.73	9.37
Lifetime Air Filter Replacement Costs	$77	$77	$41	$0
Number of Lifetime Spark Plug Replacements	1	1	1	0
Spark Plug Costs per Replacement	$34	$34	$26	$26
Spark Plug Replacement Labor per Replacement	$22	$22	$17	$17
Interval Between Replacements, years	3.75	3.75	6.21	15.62
Lifetime Spark Plug Replacement Costs	$56	$56	$42	$0
Number of Lifetime Timing Chain Adjustments	1	1	0	0
Timing Chain Adjustment Labor per Adjustment	$140	$140	$140	$140
Interval Between Adjustments, years	6.76	6.76	11.19	28.11
Lifetime Timing Chain Adjustment Costs	$140	$140	$0	$0
Number of Lifetime Front Brake Replacements	2	1	1	1
Front Brake Costs per Replacement	$80	$80	$80	$80
Front Brake labor costs per Replacement	$140	$140	$140	$140
Interval Between Replacements, years	3.00	6.01	6.01	6.01
Lifetime Front Brake Replacement Costs	$440	$220	$220	$220
Additional Scheduled Maintenance Costs at 1.191 cents per mile[b]	$1,191	$1,191	$1,191	$1,191
Lifetime Scheduled Costs	$2,600	$2,380	$1,904	$1,698
Average Annual Maintenance Costs	$346	$317	$254	$226

[a] See Table A-20 for annual miles in gasoline only and electric only modes and number of years.

[b] Represents other maintenance items that are common between CVs and HEVs. Difference between CV scheduled maintenance costs detailed in the above table and the average 2.6 cents per mile maintenance costs for compact cars found in the Complete Car Cost Guide 2000.

Table A-24
Scheduled Maintenance Costs for Mid-Size SUV using Average Driving Schedule and Nightly Charging[a]

Vehicle Type	CV	HEV 0	HEV 20	HEV 60
Engine Type	V-6	V-6	V-6	I-4
Number of Lifetime Oil Changes	16	16	10	7
Oil and Filter Costs per Oil Change	$28	$28	$28	$23
Oil Change Labor per Oil Change	$21	$21	$21	$21
Interval between Oil Changes, years	0.45	0.45	0.75	1.00
Lifetime Oil Change Cost	$776	$776	$485	$305
Number of Lifetime Air Filter Replacements	3	3	2	0
Air Filter Costs per Replacement	$25	$25	$25	$20
Air Filter Replacement Labor per Replacement	$6	$6	$6	$6
Interval Between Replacements, years	2.25	2.25	3.73	9.37
Lifetime Air Filter Replacement Costs	$92	$92	$61	$0
Number of Lifetime Spark Plug Replacements	1	1	1	0
Spark Plug Costs per Replacement	$51	$51	$51	$34
Spark Plug Replacement Labor per Replacement	$34	$34	$34	$22
Interval Between Replacements, years	3.75	3.75	6.21	15.62
Lifetime Spark Plug Replacement Costs	$85	$85	$85	$0
Number of Lifetime Timing Chain Adjustments	1	1	0	0
Timing Chain Adjustment Labor per Adjustment	$140	$140	$140	$140
Interval Between Adjustments, years	6.76	6.76	11.19	28.11
Lifetime Timing Chain Adjustment Costs	$140	$140	$0	$0
Number of Lifetime Front Brake Replacements	2	1	1	1
Front Brake Costs per Replacement	$120	$120	$120	$120
Front Brake labor costs per Replacement	$140	$140	$140	$140
Interval Between Replacements, years	3.00	6.01	6.01	6.01
Lifetime Front Brake Replacement Costs	$520	$260	$260	$260
Additional Scheduled Maintenance Costs at 3.088 cents per mile[b]	$3,088	$3,088	$3,088	$3,088
Lifetime Scheduled Costs	$4,700	$4,440	$3,978	$3,652
Average Annual Maintenance Costs	$626	$592	$530	$487

[a] See Table A-21 for annual miles in gasoline only and electric only modes and number of years.

[b] Represents other maintenance items that are common between CVs and HEVs. Difference between CV scheduled maintenance costs detailed in the above table and the average 4.7 cents per mile maintenance costs for mid-size SUVs found in the Complete Car Cost Guide 2000.

Table A-25
Scheduled Maintenance Costs for Full-Size SUV using Average Driving Schedule and Nightly Charging[a]

Vehicle Type	CV	HEV 0	HEV 20	HEV 60
Engine Type	V-8	V-8	V-6	V-6
Number of Lifetime Oil Changes	16	16	10	7
Oil and Filter Costs per Oil Change	$33	$33	$28	$28
Oil Change Labor per Oil Change	$21	$21	$21	$21
Interval between Oil Changes, years	0.45	0.45	0.75	1.00
Lifetime Oil Change Cost	$856	$856	$485	$340
Number of Lifetime Air Filter Replacements	3	3	2	0
Air Filter Costs per Replacement	$30	$30	$25	$25
Air Filter Replacement Labor per Replacement	$6	$6	$6	$6
Interval Between Replacements, years	2.25	2.25	3.73	9.37
Lifetime Air Filter Replacement Costs	$107	$107	$61	$0
Number of Lifetime Spark Plug Replacements	1	1	1	0
Spark Plug Costs per Replacement	$68	$68	$51	$51
Spark Plug Replacement Labor per Replacement	$45	$45	$34	$34
Interval Between Replacements, years	3.75	3.75	6.21	15.62
Lifetime Spark Plug Replacement Costs	$113	$113	$85	$0
Number of Lifetime Timing Chain Adjustments	1	1	0	0
Timing Chain Adjustment Labor per Adjustment	$140	$140	$140	$140
Interval Between Adjustments, years	6.76	6.76	11.19	28.11
Lifetime Timing Chain Adjustment Costs	$140	$140	$0	$0
Number of Lifetime Front Brake Replacements	2	1	1	1
Front Brake Costs per Replacement	$120	$120	$120	$120
Front Brake labor costs per Replacement	$140	$140	$140	$140
Interval Between Replacements, years	3.00	6.01	6.01	6.01
Lifetime Front Brake Replacement Costs	$520	$260	$260	$260
Additional Scheduled Maintenance Costs at 3.764 cents per mile[b]	$3,764	$3,764	$3,764	$3,764
Lifetime Scheduled Costs	$5,500	$5,240	$4,655	$4,364
Average Annual Maintenance Costs	$733	$698	$620	$581

[a] See Table A-22 for annual miles in gasoline only and electric only modes and number of years.

[b] Represents other maintenance items that are common between CVs and HEVs. Difference between CV scheduled maintenance costs detailed in the above table and the average 5.5 cents per mile maintenance costs for full-size SUVs found in the Complete Car Cost Guide 2000.

Table A-26
Market Preference Versus Vehicle Price Scenario for Compact Car Segment of Customer Survey[a]

Vehicle Type	Low Price		ANL Price		Base Price		High Price	
	Vehicle Price	Market Preference	Vehicle Price	Market Preference	Vehicle Price	Market Preference	Vehicle Price	Market Preference
HEV 0	$15,810	26.8%	$16,405	22.9%	$17,611	18.5%	$19,412	8.4%
HEV 20	$17,040	39.5%	$18,398	26.6%	$20,071	12.7%	$23,102	3.1%
HEV 60	$19,162	29.8%	$21,992	7.8%	$24,314	3.7%	$29,467	1.1%

[a] Comparisons of one HEV versus CV. CV base price $14,009. Low price scenario is 50% of the incremental cost between Base Price HEV and Base Price CV. High Price case is 150% of the incremental cost between Base Price HEV and Base Price CV.

Table A-27
Market Preference Versus Vehicle Price Scenario for Mid-Size SUV Segment of Customer Survey[a]

Vehicle Type	Low Price		ANL Price		Base Price		High Price	
	Vehicle Price	Market Preference	Vehicle Price	Market Preference	Vehicle Price	Market Preference	Vehicle Price	Market Preference
HEV 0	$33,776	43.8%	$34,890	38.2%	$36,527	32.7%	$39,279	24.8%
HEV 20	$35,277	44.0%	$37,311	37.6%	$39,529	29.8%	$43,782	14.7%
HEV 60	$37,568	36.2%	$41,039	22.9%	$44,112	12.9%	$50,656	3.7%

[a] Comparisons of one HEV versus CV. CV base price $31,024. Low price scenario is 50% of the incremental cost between Base Price HEV and Base Price CV. High Price case is 150% of the incremental cost between Base Price HEV and Base Price CV.

Table A-28
Market Preference Versus Vehicle Price Scenario for Full-Size Segment of Customer Survey[a]

Vehicle Type	Low Price		ANL Price		Base Price		High Price	
	Vehicle Price	Market Preference	Vehicle Price	Market Preference	Vehicle Price	Market Preference	Vehicle Price	Market Preference
HEV 0	$40,795	50.6%	$42,042	45.0%	$43,936	38.8%	$47,077	31.2%
HEV 20	$41,925	51.3%	$43,577	46.1%	$46,196	39.6%	$50,467	25.5%
HEV 60	$44,907	42.3%	$48,566	30.0%	$52,159	20.2%	$59,412	6.2%

[a] Comparisons of one HEV versus CV. CV base price $37,654. Low price scenario is 50% of the incremental cost between Base Price HEV and Base Price CV. High Price case is 150% of the incremental cost between Base Price HEV and Base Price CV.

Table A-29
Market Preference Versus Gasoline Price for the Base Vehicle Price Scenario[a]

Vehicle Type	Compact Car		Mid-Size SUV		Full-Size SUV	
	$1.65/gal[b]	$3.00/gal[b]	$1.65/gal[b]	$3.00/gal[b]	$1.65/gal[b]	$3.00/gal[b]
HEV 0	18.5%	24.0%	32.7%	46.5%	38.8%	54.7%
HEV 20	12.7%	19.5%	29.8%	45.6%	39.6%	57.0%
HEV 60	3.7%	7.9%	12.9%	27.0%	20.2%	41.7%

[a] Comparisons of one HEV versus CV.
[b] Gasoline price

Table A-30
Market Preference Versus Gasoline Price for the ANL Vehicle Price Scenario[a]

Vehicle Type	Compact		Mid-Size SUV		Full-Size SUV	
	$1.65/gal[b]	$3.00/gal[b]	$1.65/gal[b]	$3.00/gal[b]	$1.65/gal[b]	$3.00/gal[b]
HEV 0	22.9%	30.0%	38.2%	53.4%	45.0%	61.2%
HEV 20	26.6%	38.4%	37.6%	54.2%	46.1%	62.9%
HEV 60	7.8%	14.9%	22.9%	44.1%	30.0%	54.4%

[a] Comparisons of one HEV versus CV.
[b] Gasoline price

Target:
Electric Transportation

About EPRI

EPRI creates science and technology solutions for the global energy and energy services industry. U.S. electric utilities established the Electric Power Research Institute in 1973 as a nonprofit research consortium for the benefit of utility members, their customers, and society. Now known simply as EPRI, the company provides a wide range of innovative products and services to more than 1000 energy-related organizations in 40 countries. EPRI's multidisciplinary team of scientists and engineers draws on a worldwide network of technical and business expertise to help solve today's toughest energy and environmental problems.

EPRI. Electrify the World

Printed on recycled paper in the United States of America

1006892

EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com