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PAPER TITLE
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The Prospects for Electric and Hybrid Electric Vehicles: Second-Stage Results of a Two-Stage Delphi Study

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ABSTRACT

A two-stage Delphi study was conducted to collect information that would enable a technical and economic assessment of electric (EV) and hybrid electric (HEV) vehicles. The first-stage worldwide survey was completed in fall 1994, while the second-stage was completed by summer 1995. The paper reports results from the second round of the survey and the major differences between the two rounds. This second-stage international survey obtained information from 93 expert respondents from the automotive technology field. The second-stage response provided the following key results:

- EVs will penetrate the market first, followed by internal combustion engine powered HEVs, while gas turbine and fuel cell powered HEVs will not have any significant penetration until after 2020. By 2020, EVs and internal combustion engine powered HEVs are projected to have approximately a 15% share of the new vehicle market. They will also cost significantly (18–50%) more and will have characteristics slightly inferior to 1993 gasoline baseline cars.

- The AC (alternating current) induction motor is projected to be both technically and economically superior to the DC (direct-current) and DC brushless motors by 2020. The DC motor will be significantly less expensive in 2000, offsetting its declining technical competitiveness. DC brushless motors are projected to be the most expensive throughout the study period.

- Though generally declining significantly throughout the period, battery costs will remain high, especially for the high specific energy units.

- EVs are believed to be effective in reducing urban emissions; however, the costs of these vehicles must be reduced drastically.

- Petroleum is expected to be the predominant source of fuel for hybrid vehicles through 2020.

- The mean energy equivalent fuel economy of electric drivetrain vehicles is projected to be 20-40% greater than for conventional vehicles in 2000, and to rise a few percents during the projection period. Respondents anticipate only a 16% increase in conventional vehicle fuel economy from 2000 to 2020.

INTRODUCTION

A major goal of the U.S. Department of Energy (DOE) is to improve the energy efficiency of the U.S. transportation system by developing vehicle technologies that are also beneficial to the environment. The Office of Transportation Technologies (OTT) within DOE funds research that would increase vehicle fuel efficiency and alternative fuels use, including electricity, and thereby reduce petroleum consumption. These efforts are intended to enhance national security by reversing the growing U.S. dependence on imported petroleum, thereby improving the balance of trade and maintaining a solid foundation for sustained economic growth.

Secondary DOE research goals involve (1) developing new vehicular technologies that further improve air quality in those large urban areas that continue to suffer violations of air quality standards and (2) alleviating concerns about global warming due to burning of fossil fuels. A good transportation technology is one that reduces oil use and criteria pollutant emissions (to meet and maintain air quality standards and simultaneously reduce "net" greenhouse gas emissions) yet is no more expensive to own and operate than today's vehicle. Such cost-effective technological improvements have been made repeatedly by the U.S. automobile industry, but the goals for individual vehicles set by society continue to be made more ambitious, either to offset growth in vehicle use or to accommodate changing scientific information on the damage attributable to individual pollutants, or both. The ideal transportation technology not only accomplishes all of the above goals, but it does it to such a degree that it offsets the effects of growing travel. Further, a new long-term concern has emerged — the decline of oil production and reserves in the United States.

Although air quality in major urban areas of the United States has improved considerably over the last two decades, it has not done so at the rate projected. Further, researchers know more than ever about the deleterious effects of air pollution, leading the U.S. Environmental Protection Agency (EPA) to consider even stricter air quality standards for ozone and particulate matter than are currently on the books (Environmental Science and Technology News, March 1996).

As the responses to this survey indicate, the motivations of entities other than DOE for introducing new technologies may not be the same as the DOE's mission dictates. In particular, the focus on electric drivetrain vehicles can be traced to environmental concerns in the state of California — namely the extreme difficulty of meeting ozone standards in the Los Angeles basin.

California analyses implied that very low or zero emissions vehicles would have to be introduced if Los Angeles were ever to meet the ozone standard, while ozone concentrations in the capital, Sacramento, increased. California promulgated a regulation requiring the introduction of such vehicles (nominally, "zero emissions vehicles;" effectively, electric vehicles), spurring research and development by major auto manufacturers worldwide. The manufacturers and others argued that hybrid electric vehicles could be used to meet California's goals more cost-effectively. Although there has been considerable resistance to the regulation (and it has since been revised), the motivation remains strong to continue developing and introducing all-electric vehicles or hybrid vehicles with a limited electric-only operating capability. This technology is potentially valuable because it could help eliminate emissions in the most congested and polluted zones of numerous highly polluted cities worldwide (Walsh, various issues). Consequently, the research, development, and demonstration of electric vehicles has maintained momentum, partly as a side effect of technical developments spurred by the California regulation (Moore, 1996).

In addition to the motivation to reduce emissions and subsequent interest in electric drivetrain vehicles, the long-term concerns about global warming and domestic oil supplies contributed to the development of a partnership between government and industry: the Partnership for the Next Generation of Vehicles, or the PNGV. Goal 3 of the PNGV is to develop a performance and cost-equivalent mid-sized vehicle that can triple the fuel economy of a typical 1992 mid-sized vehicle (National Research Council, 1994). One of the technological options under serious consideration to meet this goal is the electric hybrid vehicle.

Because of the uncertainty regarding future costs and operating attributes of electric and hybrid electric vehicles, as well as the need to obtain estimates for internal planning purposes, a two-stage Delphi study was funded by the Office of Transportation Technologies of the U.S. Department of Energy. The study was conducted by Argonne National Laboratory, with the assistance of the SAE Cooperative Research Program. Expert opinions on future vehicle attributes, component characteristics, costs, and market penetration potential over the period 2000–2020 were sought. Opinions of respondents were also solicited on factors that can influence the market potential, emissions, and global warming effects of electric and hybrid vehicles.

A general summary of the Delphi survey methodology and its particular two-stage mail questionnaire variation as used in this study have been previously given in a paper (Ng, Anderson, and Santini, 1995). That paper presented selected first-stage results of the study, while this version gives a somewhat extended list of second-stage results. The earlier paper also discusses some limitations of the study design (as pointed out by reviewers) and provides estimates of the range of error that could exist for the detailed results presented. That information is not repeated here.

Results given in detail in both papers include the most important vehicle attributes (as determined by respondents), vehicle cost projections, market share estimates, and electric motor costs. As a result of U.S. DOE Office of Transportation Technology planning needs that were overlooked when the first-round survey was designed, two questions were added in the second round. These questions addressed (1) the anticipated gasoline-equivalent fuel economy of the vehicle types and (2) the anticipated fuels that would be used by the three types of hybrid vehicles included. Detailed results for these two questions are discussed in this paper, although the results are based on only one round of questioning. At the end of this paper, market penetration expectations are also evaluated by subjecting the vehicle attributes data to a modeling exercise. A number of other results are also discussed.

METHODOLOGY, BACKGROUND, AND PROCEDURE

One approach to predicting the future is to rely on published research relating to potential or projected advancements. This approach has some drawbacks because published research more often provides partial information, is occasionally dominated by a few prolific writers, and/or is more likely to be generated by advocates of a technology. Also, because of the highly turbulent state of EV and HEV technologies and decisions by the U.S. Advanced Battery Consortium to keep R&D results secret, information available on them at the outset of this study was sporadic, occasionally speculative, or based on limited analysis. Much more information is now available, and predictions are available for the next few years (Moore, 1996). However, predicting a realistic state of any emerging technology over a quarter of a century is a very difficult task, even when a lot is known about initial versions of the technology. As a result of such difficulties, especially the possible bias created by depending on published information produced largely outside of industry, a Delphi approach was chosen, taking advantage of SAE's ability to identify and solicit responses from industry experts.

The Delphi method has been frequently and reasonably successfully used for technological forecasting (Helmer, 1967; Pyke and North, 1969). One of the potential advantages of the technique is the incorporation of unpublished knowledge from the latest advancements (published research usually lags behind the current state of the technology). Pessimism can also be voiced without fear of attribution if respondents remain anonymous, as was the case in this study. It is also true that responses to similar Delphi questions vary as conditions change over time (University of Michigan, 1994). Conditions such as heightened concerns over oil price and availability or highly publicized catastrophic failures of technologies in field testing can cause opinions to change significantly, especially for short-run predictions (2000 in this case). Further, in this study, the two rounds of questions were separated by over a year of time, during which the composition of the U.S. Congress changed significantly, as did the attitude toward environmental regulation. Also, between the two rounds a respected group evaluated the state of technology for batteries for the California Air Resources Board, and published results in December 1995 (see Moore, 1996).

A two-stage Delphi study such as this is useful when convergence or a vote on an agreed-upon divergence is not needed (Delbecq et al., 1975). Responses to the first-stage questionnaire were analyzed, and information on first-round results was reported to the respondents when the second-stage questionnaire was administered. Respondents thereby had the opportunity to take into account the opinions of their colleagues. Usually, the organization conducting the Delphi study works directly with experts whose opinions are sought. However, because ANL and its DOE sponsor OTT might be perceived to have a conflict of interest arising from its participation in several EV and HEV research initiatives, ANL solicited the assistance of the Society of Automotive Engineers (SAE). SAE's involvement in selecting Delphi participants would broaden the respondent base and minimize bias. Under the arrangement, SAE administered the study and provided responses to ANL. This arrangement also ensured anonymity of the respondents because their identities were removed before the data were sent to ANL. The selection process used by SAE did include sorting the SAE member database to identify appropriate experts. The SAE database relies on self-identification of areas of expertise and interest.

The SAE Cooperative Research Program and selected SAE Committee members also provided valuable help with the structure, appearance, and question formulation/validation of the first-stage questionnaire. ANL staff drafted an initial version of the questionnaire, after which it was subjected to a thorough review by SAE. SAE's Cooperative Research group assembled a review committee of 25 persons. Members of this group familiarized themselves with the study objectives and provided comments and suggestions to make the questionnaire more effective. The revised questionnaire was further reviewed by ANL and DOE staff most familiar with the study and then pretested. An evaluation of the pretest responses was conducted for their usefulness in this and other research initiatives.

Information on vehicle characteristics, components, and system impacts was collected through the questionnaire. The questionnaire sought opinions on such EV and HEV attributes as range (engine-only and full charge plus full fuel tank for the hybrid), acceleration time (two categories), top speed, the maximum negotiable uphill grade at a sustained speed, seating and luggage capacities, curb weight, power-to-weight ratio, recharging time, and average maintenance interval. In an introductory question, respondents were asked to rate the relative importance of these attributes to consumer acceptance and marketability. They were then requested to provide expected values for each of the attributes for the years 2000, 2010, and 2020.

One way of grouping questions, instead of focusing on general opinions, is to distinguish those that asked for numbers for 2000, 2010, and 2020 from those that did not relate to time. General opinion questions covered the following: (1) providing the previously mentioned importance ratings for 11 EV attributes and 12 HEV attributes, (2) ranking the relative importance of five vehicle amenities, (3) ranking three categories of R&D, (4) indicating agreement/disagreement with 11 statements about HEVs, (5) ranking six "obstacles to commercialization" for EVs and HEVs, (6) indexing the relative recyclability and environmental impact of the 10 battery types, (7) ranking the technical performance of six materials on six performance categories, (8) indicating agreement/disagreement with eight statements on air pollution, (9) indicating agreement/disagreement with five statements on global warming, (10) ranking six explanations for the decline of support for nuclear energy, and (11) rating 12 possible keys to successful market penetration of EVs and HEVs.

Topics for which projections for 2000, 2010, and 2020 were sought in the first round of questioning included the following: (1) values for 11 EV and 12 HEV vehicle attributes, (2) costs of five vehicle types (conventional, EV, and three hybrid types distinguished by power unit), (3) fuel and maintenance cost ratios for the five types, (4) estimates of new vehicle market penetration for the five types and "other" types, (5) five technical attributes of ten battery types, (6) general technical suitability and cost of three types of electric motors, (7) technical and safety suitability and cost of five types of power units for hybrids, and (8) technical viability and cost of five EV/HEV component types. After the first round, it was recognized that fuel and maintenance cost was not enough information for DOE/OTT planning purposes, and that fuel type and fuel economy information was needed. Two more questions were added in the second round to address the following: (1) fuel economy (in gasoline mpg terms) of the five vehicle types and (2) fuel type anticipated to be used by the three HEV types (conventional internal combustion engine, gas turbine, and fuel cell).

An important point to note is that respondents were requested to solicit opinions of knowledgeable experts within their institution when they did not feel qualified to answer a particular portion of the questionnaire. An issue that emerged with the second-round responses was a set of consecutively numbered identical responses (responses were numbered by SAE in the order received). Given the requests for "within institution" discussion, it was decided to assume that these are legitimate responses resulting from internal institutional discussion of the most appropriate response. Note that the Delphi study concept allows, in certain variations, discussion of first-round results by all participants, and individuals were allowed to state a case for particular values. In this case, it is possible that one individual within an institution swayed others in that institution. Preliminary investigation indicates that, with the exception of one battery type, the inclusion or exclusion of these responses has little effect on the results. More information will be provided in an Argonne National Laboratory report on this study (in progress).

The second-stage Delphi questionnaires, containing the first-stage results, histograms, and respondent comments, were sent to the 191 respondents of the first-stage study. Responses received for the second-stage study, and judged to be legitimate, totaled 93. The composition of the second-stage legitimate respondents is shown in Table 1. The industry group was the largest, constituting 47% of the total. In the first round, industry responses constituted 52% of the total. Other experts, which should include private research organizations and potential suppliers to industry, constituted 29% of the total, up from 21.5%.

QUESTIONNAIRE ERROR/UNCERTAINTY - See Ng, Anderson, and Santini (1995) for a discussion of questionnaire error for the vehicle attributes questions and a reporting of estimated values by vehicle attribute.

OPTIMISTIC AND PESSIMISTIC FORECASTS - In a previous Argonne Delphi study of ceramic components for engines (Larsen and Vyas, 1988), the responses were divided into optimists and pessimists by dividing the sample into values above the median and below the median. The mean of values above the median was described as the optimistic response, and the mean of the values below the median was described as the pessimistic response. These statistics have been computed for this study as well. They are presented in tables in this paper and have been presented in Ng, Anderson, and Santini (1995). The nature of responses and level of accuracy of Delphi studies is briefly discussed in that paper.

HIGH AND LOW QUARTILE VALUES - The typical measure of uncertainty used in Delphi studies is the quartile range (see, for example, University of Michigan Transportation Research Institute, 1994). Ascher (1987) terms the low quartile value as the low forecast and the high quartile value as the high forecast. The low quartile value is the median of all values below the median, while the high quartile value is the median of all values above the median. This measure is in contrast to the optimistic and pessimistic forecasts used here, which use means of the values on an appropriate side of the median. Note that "low" and "high" would be deceptive terms in this analysis, because some vehicle attributes are to be increased (such as range, maintenance interval, and maximum uphill grade), while others are to be reduced (such as acceleration time, cost, and recharge time). We attach a meaning and order to our "optimist" and "pessimist" values in the tables and report the interquartile range, a commonly used statistic for reporting uncertainty in Delphi results, in a similar order. The interquartile range is the difference between the reported quartile values and is a measure of dispersion. Where discussions below address the dispersion of responses, we base statements on the interquartile range. When comparing the first- and second-round results, we do not apply a correction for sample size. Use of the median instead of the mean is recommended by Ascher, as is the use of the interquartile range instead of the standard deviation. The use of the interquartile values eliminates the influence of outlying observations, preventing a small proportion of respondents from having a disproportionate effect.

In the case of vehicle attributes in our study, the method of suggesting a range of values, rather than asking for point estimates, tended to reduce the likelihood that extreme values would be entered into the sample. Thus, use of averaging to estimate the optimistic and pessimistic values is not as problematic for those questions as it might otherwise be.

In other types of questions, the respondents were asked to provide a point estimate or to select a number for purposes of estimating an ordinal ranking. Questionnaire error was not a problem, but the inclusion of extreme values in the computations of optimistic and pessimistic values was more likely to be a problem. For example, in battery questions, a number was requested, and a reference value for current technology was provided. Accordingly, we present only the interquartile values for selected batteries. For the remainder of the questions requesting ranking or ordering, we simply discuss mean values in the text, or discuss the ordering established without presenting numerical results.

SURVEY RESULTS ON ELECTRIC\HYBRID VEHICLES

QUESTIONNAIRE SECTIONS - The questionnaire was divided into three main sections containing (I) general questions on the vehicle, (II) detailed questions on vehicle components, and (III) questions about system impacts. The intent was to help the experts go to the section(s) with which they are most familiar and leave the other sections to their colleagues. However, in this two-stage study, we estimate that more than 90% of the respondents did not ask their colleagues for assistance (estimate was based on the different handwriting on the same questionnaire); instead, they left some of the sections unanswered. The component section had significantly fewer answers than did the other two sections, indicating that respondents were willing to provide projections of vehicle performance and market share, even when they did not believe that they could accurately predict component characteristics.

Vehicle Characteristics - The vehicle characteristics section asked the respondents, first, to rank the eleven (or twelve) most important vehicle attributes by using a rating of one to ten. The experts had the opinion that the five most important EV attributes were (in order) the range, maintenance interval, recharging time, 0–50 kph acceleration, and maximum uphill grade for which a 75-kph speed can be maintained. Aside from a switch of maintenance interval and recharging time, this order is identical to the first round. The three least important attributes were (in order, starting with the least important) the top speed, unladen vehicle weight, and cargo space. Weight, space, and speed were the results from the first round. For the HEVs, the five most important attributes were the total range, engine range, maximum uphill grade for which a 75 kph speed can be maintained, maintenance interval, and 0–50 kph acceleration. From the first to the second round, engine range jumped from sixth to second, while the order of importance of the other four attributes was otherwise unchanged.

The fact that most people still felt that engine range was important is probably due to their confidence in the internal combustion engine and a lack of faith in the battery. This anxiety will probably disappear in time. However, respondents to the second-stage questionnaire ranked engine-alone range second up from sixth in the first-stage questionnaire. This change seems to indicate a loss of faith in battery technology from 1994 to 1995. The three least important attributes were the unladen vehicle weight, recharging time, and cargo space. Ranking recharging time as unimportant for hybrids seemed to indicate that most people assumed that onboard charging will be the preferred charging scheme in the HEVs, thus making recharging time less important. The HEV range question implies that the time required to fully charge an HEV from the grid would take almost as long as it would to charge an EV, although the consumer might not choose to fully charge from the grid except during times when air pollution would be a concern. For those who answered both the full range and engine range question for HEVs (in 2000), the answers were 364 km and 215 km, implying an all-electric range of 149 km, only 30 km below the EV range question. Because average daily travel is about 48 km, it could be argued that the HEVs specified by the respondents have a longer all-electric range than what would be needed if the vehicle had to be driven under electric power during an air pollution episode.

The California Air Resources Board (CARB, 1995a) has proposed (and since modified) regulations that required the introduction of zero emissions vehicles (ZEVs). A portion of this "Low Emissions Vehicle (LEV)" regulatory package required ZEV introduction and sales by major manufacturers in quantities equal to 2% of California sales in 1998, rising to 10% in 2003. As a result of pressure from automakers, CARB proposed a regulation amendment to give HEVs a proportional credit toward meeting the ZEV requirement of the LEV regulation. The July 1995 proposal would require that HEVs have no less than 48 km of range before being allocated a minimum "ZEV-equivalent" credit equal to 34% or 68% of a ZEV, depending upon design restrictions on the hybrid. These percentages applied to the range category from 48 to for HEVs with 48 to 63 km of "all-electric" range. Percentage credits increased for 16-km categories, rising rapidly to 83% or 41% for a range of 97 to 111 km and peaking at 88% or 44% for an all-electric range exceeding 145 km (CARB, 1995a).

The automobile industry's concept for the PNGV vehicle (Office of Transportation Technologies, 1995; U.S. Congress, Office of Technology Assessment, 1995) is quite different from the vehicle that the CARB would induce manufacturers to produce if the proposed LEV amendment were to be approved. Goal 3 of the PNGV is to produce a mid-sized passenger car with triple the gasoline-equivalent fuel economy of a 1995 baseline vehicle (defined as a composite of the Ford Taurus, Chevrolet Lumina, and Chrysler Concorde) and having the same performance capabilities, with a life-cycle cost no more than the baseline vehicle. Goal 3 of the PNGV to triple gasoline-equivalent miles per gallon requires a far different design strategy than the CARB goal of minimizing emissions by maximizing all-electric range. In fact, given the specific power vs. specific energy of batteries that are anticipated to be available in 2000, the PNGV design goal is to keep the battery pack size of the HEV as small as possible. Given minimum power requirements, this goal can theoretically be achieved with a battery pack that will give an all electric range of less than 48 km (U.S. Congress, Office of Technology Assessment, 1995). Because the average U.S. car is driven about 48 km/day, including vacation trips, an argument can be made that an HEV with less than 48 km of all electric range should deserve a ZEV credit, and such an argument has been presented to CARB by the automobile industry and others (CARB, 1995b).

HEV is a term that covers a wide range of design possibilities. A full discussion of these options is well beyond the scope of this paper, and, due to questionnaire complexity and length limitations, it was not possible to ask multiple questions directed at opinions about various HEV design philosophies.

Designers and testers of HEVs have divided them in several ways. One categorization (Penney, Christensen, and Poulos) distinguishes between HEVs on the basis of the amount of all-electric range and whether the HEV is charge-sustaining or charge-depleting. For an organization that wishes to assure that an HEV will normally be charged from the grid and start the day in all-electric operation, the incentive will be to demand an HEV that performs significantly better when fully charged and that cannot use its fuel engine during normal daily operation to keep the battery pack state of charge (SOC) constant. Because the vehicle would perform poorly when dependent on the fuel engine, the incentive would be to charge it each evening to keep the SOC high. The reason for the fuel engine is to inexpensively extend the range of the hybrid to allow it to be more marketable to persons concerned about occasionally using the vehicle for long trips. This type of HEV is often called a range extender. It has a considerable all-electric range and is charge-depleting; the fuel engine is used only to extend the range for unusual conditions.

The PNGV concept is a charge-sustaining, low-range, all-electric HEV. With this concept, the HEV battery pack will never require charging from the electric utility grid. Its performance will be relatively constant in comparison with a range-extender HEV, even though there would be variation dependent on the state of charge and age of the battery pack.

A question that we asked ourselves is whether the respondents had in mind the range-extender HEV (say RE/HEV) or the PNGV type of HEV. Because the only distinctions among HEVs requested were type of power unit, this question had to be addressed indirectly. We decided to approach this question by examining the ratio of engine-only range to full range specified by the respondents. This value would, in principle, be 1.0 if the electrical energy-storage system had zero capacity. In principle, such an answer might be given by individuals predicting success for a fuel-cell vehicle, because such a vehicle can be designed without an electrical energy-storage system, but it will be an electric drivetrain vehicle. If the ratio were 0.0, the vehicle would be an electric (no such responses were recorded). We presumed that a PNGV/HEV would have to have a reasonable range. By sorting the responses by year 2000 engine-only range to full range for those responses where the full range was equal to or more than 350 km, we found that only 12 of the 88 respondents characterized the year 2000 HEV within these limits. For the 12, the average all-electric range in the year 2000 was estimated to be less than 50 km (questionnaire construction does not justify any further indication of preciseness). For the remaining 76 respondents who answered both range questions, the average all-electric range for the year 2000 is estimated to be about 150 km. In spite of this relatively large difference in the estimates of all-electric range by these two subgroups, the differences in the characterization of the vehicles in other respects were not very great. In particular, the reduction in average or median mass for the years 2000 and 2010 estimated by the 12 respondents was 100 kg or less when compared with the remaining 76. The most frequent mass estimate (the mode), however, was 400 kg greater for the 76 respondents than the 12 in the year 2000, narrowing to no difference in 2010.

Perhaps the most striking observation from this experiment was the closure of the differences in estimated all-electric range from 2000 to 2020. The "PNGV-type-12," which estimated that all-electric range would only be about 50 km in 2000 (mean estimate = 25 km; median and mode = 50 km), estimated that all-electric range capability would increase to 200-250 km (mean estimate = 200; median and mode = 250) by 2020. The 2020 estimate for the "range extender" group was 150 to 250 km (mean estimate = 255; median and mode = 150). The year 2020 vehicle range estimates by the PNGV-type-12 (mean = 600; median and mode = 650) were also higher than those for the remainder (mean = 510; median and mode = 400). In most other respects, the vehicle characteristics given by these two groups were not large enough to warrant separate presentation or discussion. Given the otherwise identical characterizations, the PNGV-type-12 can be regarded as even more optimistic about electric storage component capabilities than the remainder of the respondents. By 2020, the consensus of these respondents appears to be that it would be possible to have an HEV technology that could, if necessary, use electricity from the grid for nearly all miles of travel, except for vacation miles and other intercity trips. Those respondents who believe that a vehicle produced in the year 2000 will have to minimize the amount of all-electric range expect that problem to disappear by the year 2020.

Forecast statistics for the five most important EV and HEV attributes are presented in Table 2. In general, these projections are more pessimistic than those in the first-stage study. Relative to first-round results, the degree of pessimism in the shortrun (year 2000) is greater than in the long run (years 2010 and 2020), with the 2020 values generally close to the first-round estimates.

The exception, however, is for maintenance interval. Second-round respondents generally estimated an extension of the maintenance interval. The range of the estimated maintenance interval also narrowed. Maintenance intervals estimated for EVs are longer than those for HEVs.

Three vehicle characteristics can be compared to the PNGV goals. One of the PNGV performance goals is acceleration from 0 to 96.5 km/h in 12 s. This questionnaire asked respondents to estimate 0–50-km/h and 50–100-km/h acceleration separately. The simplified question does not specify whether the 50–100 km/h time is to be estimated from a start at a steady 50 km/h or as a part of a 0–100-km/h acceleration run. All other things equal, those respondents using the latter interpretation would estimate a faster time. The mean estimate of 0–100 km/h acceleration time for the HEV, developed by adding the two responses together is 15 s, in 2010 and 13 s in 2020. Obviously, a large proportion of respondents believe that the PNGV acceleration goal is possible, although perhaps not as soon as desired (between 2000 and 2010). Roughly speaking, using mean results, respondents projected EVs to be about 1 s slower than HEVs to 50 km/h (Table 2). Mid-sized vehicles of 1995 vintage accelerate faster than the 2020 estimates for HEVs and EVs, generally from 0 to 96.5 km/h in under 10 s (Consumer Reports, January, 1995). Minivans, however, have acceleration times of about 12 s (Consumer Reports, October, 1995 and December, 1994).

Another PNGV performance goal is an ability to climb a 6.4% grade at 88.5 kph for 20 min. In the questionnaire, no detailed specifications were given for the gradeability question. The request was for an estimate of the maximum uphill grade for a sustained speed of 75 kph. The mean response in 2000 for HEVs was less than that for the PNGV goal, even for the lower speed (Table 2). The year 2010 and 2020 estimates at 75 kph, however, did exceed the PNGV goal for 88.5 kph. By 2020, the median and modal responses, at 11%, are well in excess of the PNGV goal and imply that, even at 88.5 kph, the goal could be met by a hybrid.

By the year 2020, the mean curb weight estimated by the respondents is about 1,300 kg for both EVs and HEVs. By comparison, the average mass for the 1995 Lumina, Taurus, and Intrepid is 1,525 kg (Consumer Reports, Jan. 1995), a reduction of about 15%. This is less than the estimates of required mass reduction made by PNGV analysts. Consistent with this "pessimistic" estimate of the potential for mass reduction, the respondents do not estimate that the goal of tripling fuel economy can be attained. In fact, the respondents as a whole are quite "pessimistic" in this regard, estimating fuel economy gains of about 50% by 2020 (Table 3). Even the optimists, as we define them, do not project tripling fuel economy, although they do expect ICE HEVs to be able to double fuel economy (relative to 2000), while EVs, gas turbine HEVs, and fuel cell HEVs are projected to be capable of increasing fuel economy by about 2.5 times. An interesting result of the fuel economy question is that the typical respondent does not expect much improvement and may even expect deterioration. Those we would term "pessimistic" are indeed pessimistic, predicting declines in fuel economy from 2000 to 2020 for all types of vehicle examined in the survey.

Respondents inferred considerable improvement in "packaging efficiency" for EV and HEV components. Although mass was projected to decrease, passenger and cargo room was projected to increase. The mean number of seats projected by the respondents for the vehicles that they had characterized increased from 3.4 in 2000 to 4.6 in 2010 for EVs and 3.8 in 2000 to 5.0 in 2010 for HEVs. For cargo space, the comparable values were 220 L in 2000 and 340 L in 2020 for EVs and 240 L and 370 L for HEVs.

Cars often do not succeed in the marketplace without additional amenities for occupant comfort, safety, and aesthetics. A question concerning the importance of amenities indicated that air conditioning, compartment heating and window defrost, and premium safety equipment were considered more important than power auxiliaries and audio entertainment. These results are consistent with an interpretation that the power drain for air conditioning and heating is regarded as a critical problem, while the other amenities could more easily be designed into EVs and HEVs without significantly affecting range.

R&D AND COMMERCIALIZATION

Battery (energy density, operating temperature, materials) and energy storage technology (ultracapacitors, flywheels), vehicular technology (body, chassis, steering, and suspension), and component technology (motor, drivetrain, and regenerative or mechanical braking) are the three major concerns in R&D aimed at commercialization of EVs and HEVs. The respondents were requested to chose the areas that will require the greatest share of R&D before these vehicles can be successfully marketed. Battery/energy storage technology, a most rapidly changing technology area, received the most votes from the respondents. Vehicular technology would require the least R&D share, according to the respondents. This finding seemed to indicate that most experts are quite confident that present automotive vehicular technology can be readily transferred to EV and HEV vehicular technology.

Eighty-three percent of respondents agreed that HEVs will be commercialized as a viable alternative to gasoline vehicles in the long term (beyond 2005), while 94% agreed that they will have operating range extended by more than 150 km compared with EVs. Almost all respondents (98%) believed that HEVs could meet the U.S. Tier II emissions standards if required for MY2004 and later automobiles. Less than one-quarter of the respondents expected the HEVs to be less expensive than EVs when commercialized. Only 8% of respondents agreed that HEVs will never be a viable alternative.

Consistent with the observations that we developed when breaking out the "PNGV-type 12" from the remainder of the respondents, only 29% of respondents thought that HEVs would *not* need electricity from the grid. While this fraction is a bit higher than we would have guessed, on the basis of the technology break category used to define a PNGV-type response, it is nevertheless reasonably consistent with that division of respondents, which was based on technical specifications of the vehicle attribute response.

Numerous recent studies have estimated that EVs and HEVs can cost significantly more than their gasoline counterparts. The experts of this study ranked two obstacles to commercialization as very important for both EVs and HEVs: (1) sales volume is too low for economical production and (2) the cost and complexities associated with manufacturing the batteries and drivetrains needed to produce attractive vehicles are high. Nevertheless, government R&D support for these vehicles was not deemed "inadequate."

COST ESTIMATES

The respondents were asked to provide the estimates of the purchase price ratio for each of the five EV\HEV types and were also asked to describe how they arrived at these values. Several respondents provided a detailed description of their estimate, while a few admitted that they used professional judgment. The majority of the respondents provided estimates but did not give any description of their cost analysis in the space provided for additional discussion/explanation.

The purchase prices of the EVs and HEVs were projected to be consistently higher than the conventional gasoline-fueled baseline passenger vehicles, but the projected values tended to be "flat" for EVs and internal-combustion-engine hybrids (ICE HEVs), while conventional vehicle prices were projected to rise (Table 4). However, only by 2020 would the EVs and ICE HEVs have competitive prices (18% and 26% more expensive than gasoline vehicles, respectively, based on means). Both the gas turbine and fuel cell HEVs were projected to cost two to three times the price of gasoline vehicles in 2000, but this ratio dropped very significantly through 2020. However, the projected prices for the gas turbine and fuel cell HEVs (52% and 97% higher than gasoline vehicles, respectively) would make these vehicles quite unattractive in 2020. The respondents seemed to firmly believe that EVs would be more expensive than gasoline vehicles, while HEVs would be more expensive than EVs in any projected period.

The second-stage price projections for the EVs and HEVs were generally higher than the first-stage projections, while the mean estimated cost of conventional vehicles dropped slightly. Among the types of electric drivetrain vehicles, the increases in cost relative to the first round were similar, except for the fuel cell vehicle, the cost estimates for which increased by a noticeably higher amount. The average increases of means, mode, and median, averaged over 2000, 2010 and 2020, ranged from 0% to 20% for the EV, ICE HEV, and Gas Turbine HEV group, while the average for the conventional ICE vehicle ranged from -7% for the mean to +9% for the mode. For the fuel cell HEV, the average ranged from 22% for the mean to 78% for the mode. The interquartile range and the difference between optimistic and pessimistic projections generally declined, with three notable exceptions. For gasoline vehicles in 2000, there was essentially no change, while for fuel cell HEVs in 2010 and 2020, the dispersion of estimates increased.

The projected fuel and maintenance costs were more favorable to EVs by 2010 and beyond. For 2000, the projected fuel and maintenance costs for EVs were higher than those for gasoline vehicles, indicating that EVs will have to go through the normal product-debugging period. However, by 2010, the projected fuel and maintenance costs for EVs are slightly lower than those for conventional vehicles and noticeably lower in 2020. All the HEVs would have estimated cost significantly higher than both EVs and gasoline vehicles throughout the projected period. Of the three HEV types, the internal combustion engine HEVs had the lowest projected fuel and maintenance cost.

The respondents were also asked (in the second round only) to indicate the type of fuel they had assumed for the three types of HEVs. According to the experts, gasoline will be the predominant fuel for the internal combustion engine HEVs, and diesel\kerosene\jet fuel will be the predominant fuel for gas turbine HEVs (Table 5). For the fuel cell HEVs, the respondents projected that either alcohol or pure hydrogen will be the preferred fuel. These projections, of course, will affect the fuel cost of these hybrid electric vehicles.

MARKET PENETRATION

We specifically asked the respondents to estimate new vehicle market share for each vehicle type so that the shares total to 100%. Essentially all of the experts predicted that conventional ICE vehicles will be the dominant vehicles in the new vehicle market even by 2020 (Table 6). Whether one uses the mean, median, or mode, such vehicles are still projected to have about 80% of the new vehicle market. One exceptional respondent felt that gasoline vehicles will shrink to a mere 10% share by 2020, while fuel cell HEVs and ICE HEVs will have 20% and 60% market penetration, respectively. Most experts did not express such a view.

Note that the market share estimates are for new vehicles, not the fleet. Because fleet turnover takes a long time, a rising share attained by new vehicles will not be matched by the fleet for a long time (Mintz et al., 1995). Thus, the proportion of conventional vehicles that will be in the entire fleet of vehicles held by households, business, and others in 2000, 2010, and 2020 would be considerably greater than that indicated by the new vehicle market share presented here.

These experts seemed to tell us that EVs will be coming to the marketplace at a rather modest pace, going from a 1% market penetration in 2000 to 7.5% by 2020. Only a few respondents believed that EVs will not make it to the marketplace, while the majority estimated fairly modest penetration. Almost 40% of these respondents projected that EVs will have better than 10% market penetration by 2020.

Of the three types of HEVs, the ICE HEVs received the most votes of confidence from the respondents. These experts projected, according to the mean estimate, that ICE HEVs will have almost 8% market penetration by 2020, slightly higher than that of the EVs. Almost 30% of these respondents projected that ICE HEVs will have better than 10% market penetration by 2020, while 12% of the respondents had projections of 20% and higher. This projected market penetration pattern of the ICE HEVs was noticeably different from that for the EVs. The spread of estimates for ICE HEVs was wider than that for EVs, with ICE HEV optimists more optimistic than EV optimists and HEV pessimists more pessimistic than EV pessimists.

If one uses the interquartile range as the basis, the uncertainty of estimates of EV market share increased from the first to the second round, while the uncertainty of ICE HEV market share estimates decreased. If one uses the spread between optimistic and pessimistic values as the measure, the uncertainty of both the EV and ICE HEV market share estimates decreased. The optimists for both types decreased their market share estimates. However, the higher quartile values remained unchanged in 2010 and 2020. The pessimistic results with respect to EV market share remained essentially unchanged, but the pessimistic results for ICE HEVs indicated a larger market share. Although the mean 2020 share estimate for EVs dropped in the second round the mode and median remained unchanged, while for the ICE HEVs in 2020 the mean remained unchanged and the *median and mode increased.*

Both gas turbine and fuel cell HEVs will not have any significant market penetration until 2020; even then, penetration will be about 3% each, according to the mean estimate of the survey respondents. Given that the gas turbine is relatively old technology compared with the fuel cell (capturing nearly all of the aircraft market and a significant segment of the power generation market), these respondents' estimates for the prospects for fuel cell HEVs can be interpreted as being relatively promising. Nevertheless, almost 40% of the respondents believed that even by 2020, neither of these two types of HEVs will be in the market. Only about 10% of the respondents projected a better than 10% market penetration for these two types of HEVs, and these estimates contribute disproportionately to the 3% penetration. In comparison to the first-stage market penetration projections, the second-stage responses for gas turbine and fuel cell HEVs are more pessimistic. By using either the interquartile range or the difference between optimist and pessimist values as the basis for measure of convergence, the second-round estimates of market share have converged, with the largest magnitude of the convergence attributable to a decrease of the high quartile value and the optimist estimates.

COMPONENTS

In the forecasting of battery types, it is important to note the number of respondents per question about battery type was far lower than the number of respondents for other questions in the survey. Apparently, the respondents did not wish to make uninformed estimates and confined their responses to those batteries for which they had some expertise and knowledge. However, a far greater response *percentage* was obtained from the second stage of the survey than from the first stage of the survey (this does not necessarily indicate a higher count in the second round, nor does it indicate that those in the first round who had answered battery questions were significantly more likely to respond to the second round). This finding indicates that the second-stage respondents, on average, perceive themselves to be more knowledgeable and have wider expertise than the first-stage respondents. A characteristic of multiple-round mail-out Delphi studies is that respondents less concerned with the outcome of the survey and/or less certain of the importance of their response will drop out in the later rounds. Unfortunately, we did not provide a simple response form that would allow first round respondents to simply indicate agreement or disagreement with the first-round results (such a form, however, might have reduced second-round response to such a degree that the additional questions asked would have lost their usefulness).

The survey requested information for 10 battery types. The number of responses ranged from a minimum of 20 for nickel-zinc and zinc bromide batteries to a maximum of 54 for lead-acid batteries. In our discussion, we will confine ourselves to the five battery types with 36 or more responses. The five types are lead-acid, nickel-cadmium, nickel-metal hydride, sodium-sulfur, and lithium-polymer (number of responses = 54-55, 43-45, 42-43, 39-41, and 39-41 respectively). The first four of these types highlighted in the summary of the CARB's Battery Technical Advisory Panel Report (Moore, March/April, 1996), along with the lithium-ion and sodium-nickel chloride battery types. Information on the latter two battery types was not requested in this study, and the respondents did not provide data on additional types. The first four of the five types discussed here are used in either commercial EVs or EV prototypes, while the lithium-polymer battery is a long-term technology, and expert respondents expect dramatic improvement. For the batteries, only broad results based on overall means, medians, and interquartile values will be discussed, while median and interquartile values are provided in Table 7.

Ongoing research and development in batteries will continue to benefit electric vehicle and hybrid vehicle applications. Mean estimates by respondents suggest that in 2020, at 172 Wh/kg, the lithium- polymer battery will have about 3.5 times the specific energy of the lead acid battery; at 8.19 yr, it will have almost twice the shelf life; at 1185 charge/discharge cycles, it will have about a third greater cycle life; and at $ 296/kWh, it will have only about 1.6 times the initial cost of the lead-acid battery. Clearly, if these forecasts are correct, this battery would be far superior (on a life-cycle cost and vehicle performance basis) to the lead-acid battery.

The ordering of specific power estimates (at 50% depth of discharge) in 2000 in this study did not match up to the specific power estimates given by CARB's Battery Technical Advisory Panel, at least according to the figure provided by Moore (1996), which did not state the depth of discharge at which the rating was given. The high value in the interquartile range indicated that all five of the battery types could meet the USABC mid-term goal of 150–200 W/kg, although none could exceed it (contradicting the Battery Technical Advisory Panel's more optimistic estimates for sodium sulfur, nickel metal hydride, and lead acid batteries in the 1996–2004 time frame). The median estimates in this study indicated that nickel cadmium and nickel metal hydride batteries could meet the USABC mid-term goal in 2000, while the mean estimates indicated that lead acid batteries could do so in addition to these two. By 2020, using means, the nickel-cadmium, nickel-metal hydride, lead-acid, and lithium-polymer batteries are all projected to have similar specific power (193–214 W/kg), which is better than that of the sodium-sulfur battery (= 160 W/kg). None of these estimates, nor the median estimates, meet the USABC long-term goal of 400 W/kg. High quartile values, ranging from 170 to 200 for the five battery types, are also well below the USABC long-term goal. Moore (1996), however, indicates that sodium sulfur and lead acid batteries should be able to meet the USABC long-term goal, at least in the graphic presented (see p. 10 of Moore).

The lithium-polymer battery is forecast in 2020 to have considerably greater specific energy (= 172 Wh/kg) than the other four, with the order for the remaining four being sodium-sulfur (= 107 Wh/kg), nickel-metal hydride (= 89 Wh/kg), nickel-cadmium (= 62 Wh/kg), and lead-acid (= 48 Wh/kg). The ordering of specific energy estimates is the same, as determined by the CARB's Battery Technical Advisory Panel Report. However, even using the high quartile values (Table 7), these respondents appear to be somewhat more pessimistic for the year 2000 than the Battery Technical Advisory Panel for the period 1998–2004 (Moore, 1996). On the basis of the high quartile values, only the lithium polymer battery is estimated by 2020 to meet the U.S. Advanced Battery Consortium's long-term goal of 200 Wh/kg, although the mean and median values (≈ 170 Wh/kg) are also close. This value is considerably more optimistic than any value projected by Moore (on p. 10), but it is projection that goes farther into the future than that considered by Moore.

Compared to many of the statistics presented in Tables 2-6, the interquartile range of the specific energy and specific power estimates relative to the median is "tight." In other words, the range of estimates is narrow relative to the average value, indicating certainty and confidence on the part of respondents. For the cycle life and cost estimates, however, the range of estimates is often wide relative to the average. Compared to respondent estimates for other batteries, respondents providing estimates for the promising lithium polymer battery appear to be most certain about cycle life and least certain about cost (Table 7).

Cycle life (discharge/charge at 50 % DOD) for the four alternatives to lead-acid is forecast to be up to two times that of current lead-acid batteries, while shelf life is also forecast to be as much as double that of current lead-acid batteries. Although the shelf life and cycle life of lead-acid batteries are also projected to improve, the lead-acid is forecast to lag behind the other four types. For the year 2000, the ordering of mean and median cycle life estimates from shortest to longest is lithium polymer, lead acid, sodium sulfur, nickel metal hydride, and nickel cadmium (with the last two tied on the basis of medians). For the latter four battery types, which are covered by the USABC Advisory Panel, the order is the same, except for a reversal of the last two. The values are generally similar. Each of the four is estimated to meet the USABC mid-term goal of 600 cycles in 2000. The order of values in 2020, by using means or medians, is as follows: lead acid, sodium sulfur, lithium polymer, nickel metal hydride, and nickel cadmium. By 2020, the last four meet the USABC long-term goal of 1000 cycles, on the basis of median estimates, while the last three do so on the basis of mean estimates. Although Moore's graphic indicates that nickel metal hydride and nickel cadmium could achieve a cycle life of 2,000 cycles by 1998–2000, none of the high quartile values developed from the responses reaches such a value, even by 2020 (Table 7).

By 2020, three of the five batteries are forecast (by use of means) to have costs ranging from $400 to 300/kWh (from most to least expensive — nickel-metal hydride, sodium-sulfur, and lithium-polymer), while the lead- acid battery is forecast to cost approximately $180/kWh, and the nickel-cadmium battery is expected to cost almost $500/kWh. If ranked by medians, the order is the same, but the alternatives to the lead- acid battery are closer to its cost. Thus, only the lead acid battery approaches the "fully mature, learned-out (the term used by CARB), commercial production" minimum of $150/kWh at a production scale of 100,000 batteries per year, as estimated by the CARB Advisory Panel (Moore, 1996). However, by using the low quartile values, all but the nickel cadmium battery are estimated to be in the neighborhood of $150/kWh (Table 7), and the lithium polymer battery, at $125/kWh, is estimated to come close to the USABC long-term goal of $100/kWh.

Lead-acid and zinc air batteries were considered the most recyclable, and zinc bromide and lithium-iron disulfide batteries were considered the least recyclable. The zinc air battery was also estimated to have the least negative environmental impact, while zinc bromide and nickel-cadmium had the most negative environmental impact rating.

The weight of vehicular propulsion battery modules will be in the hundreds of kilograms, or as much as one-third of the vehicle curb weight, indicating a significant materials-disposal problem at the end of the module's life. Lead-acid and nickel metal hydride batteries were considered the most recyclable, and zinc bromide and lithium iron disulfide were considered the least recyclable. The zinc air battery was also estimated to have the least negative environmental impact, while zinc bromide and nickel cadmium had the most negative environmental impact rating.

The match between motor technology and the propulsion battery system will be of great importance to the ultimate success of EVs and HEVs. The respondents were asked to rank three candidate motors — the direct-current, AC induction and DC brushless motors — in terms of technology and cost. By 2020, according to the experts, the AC induction motor will have the highest technology ranking and the lowest cost of the three motor types (Table 8). The cost of direct current motor will be as competitive as the AC motor, but the technology will be behind both the AC induction and brushless motors. It should be noted here that, the motor control technology is also an important element in both EVs and HEVs technology. No questions on motor control technology were included in the survey. Recent progress in control technology warrants future survey attention.

Electric and hybrid vehicle design goals include low vehicle weight without sacrifice in occupant safety. Advanced materials may be good candidates for helping to achieve these goals, and EV\HEV production may, in turn, stimulate development and accelerate commercialization of advanced materials. The respondents were requested to rank five candidate materials in terms of environmental benefit, corrosion resistance, crashworthiness, reliability, durability, and cost-effectiveness. High-strength steel was considered the best candidate, followed by aluminum, plastics, composite materials, and ceramics, respectively, while powdered metal was rated the lowest of the six categories. Ceramics had the lowest ranking in crashworthiness, reliability, and cost-effectiveness.

SYSTEM IMPACTS

Most (93%) of the experts had the opinion that EVs will help reduce ozone levels in urban areas, because of the displacement of gasoline combustion and storage by fuels or energy production techniques with lower ozone-forming potential. More that 90% of the experts believed that most EV charging will use overnight base-load capacity, resulting in little net increase in daytime power plant emissions. Close to 90% agreed that EVs will be environmentally beneficial because of the displacement of emissions from urban areas to remote power plants and from daytime to nighttime. Moreover, any increase in power plant emissions due to EV use will be offset at the local level by decreases in on-road emissions. About one-half expected coal to be the predominant power plant fuel. Less than (but close to) one-half expected that electricity will be generated from natural gas, low-carbon-per-kW fuels, and nuclear sources.

Less than one-half (44%) of the respondents believed that EVs and HEVs will reduce the potential for global warming by 2020, even if these vehicles have a market share of 33% (study mean projection, 21%). More than 80% of the experts had the opinion that the complexity of global warming as a scientific issue requires that many more studies must be undertaken before any key policy decisions are made, but they also agreed that mitigation of global warming potential could have significant socioeconomic benefits. Only 16% of the respondents felt that global warming is unimportant, and future decisions on transportation policy should not have to consider it.

Most respondents had the impression that nuclear energy has a negative public image because of accidents or near accidents in the United States. The consensus was that nuclear power is less acceptable in the United States than in Europe and Asia because of disagreements about the relative costs and environmental benefits of nuclear, fossil, and renewable plant technologies, including the costs of residuals disposal.

At the end of the questionnaire, the respondents were given 12 statements for which an importance ranking was to be provided to indicate what is most important for the EVs and HEVs to succeed in the market. The intent was to give the experts the opportunity to express the context for their estimates of the technical, cost, and market penetration values they had projected for EVs and HEVs. This might also have made them rethink their answers to the questions in other sections. The experts ranked as highly important the statement that (1) these vehicles must have lower acquisition and operating costs and (2) they must be as reliable as gasoline vehicles. They also ranked highly a statement that there must be enough R&D to ensure an excellent product. Supporting infrastructure, key technology implementation, and the public perception of urban air pollution as a severe problem were all ranked as important factors, but slightly less so than the prior three. Very few believed that a new oil crisis will have to occur for these vehicles to succeed in the market. *The statement to this effect received the lowest importance ranking among the 12 statements*, with a large difference its ranking statistic relative to the next lowest ranking. The respondents seemed to be indicating that they felt that the improvement of the environment would be the driving force behind introduction of EVs and HEVs, *not* energy security. This final "statement" by the respondents was entirely consistent with the kinds of HEVs that they characterized, as we have seen.

MARKET PENETRATION ANALYSIS

In addition to the new technologies examined in the study — EV, HEV powered by a conventional (gasoline or diesel) reciprocating engine, HEV with a gas turbine, and HEV with a fuel cell — an additional category — "other technology not named above" — allowed respondents to specify shares for any other technology vehicles. As an extension of this study, we conducted a market penetration projection based on a statistical model by using the mean survey responses of each individual respondent. The analysis involved fitting of mathematical models to the survey data and computing future market shares.

MODEL ESTIMATION

The respondents specified market shares for three years. These shares varied between respondents and technologies. Mean values of these points represented aggregate opinions and may not conform to a classical market-penetration pattern. Also, a mathematical model would be useful to estimate market penetration during the intermediate years, as well as to project penetration further into the future (DOE/OTT planning exercises do involve projections to 2030).

Marketing professionals frequently use models of technology substitution. Research has shown that such market penetration follows an S-shaped curve (Mansfield, 1961; Blackman, 1974, Paul, 1979; Teotia and Raju, 1986). We used a formulation in which functions $F_o\{t\}$ and $F_n\{t\}$ define market shares of old and new technologies at time t. Note that $F_o\{t\}$ equals $1-F_n\{t\}$. We used the following logistic function also previously used by Santini (1989):

$$t = \delta + \beta \ln[F\{t\}/(1 - F\{t\})] + \mu, \qquad (1)$$

where δ and β are coefficients that become scalar factors determining the shape of the market penetration curve, and μ is the error term. The term δ defines the midpoint in time for a symmetric logistic curve, and β determines the rate at which the market is penetrated

Initially, we estimated coefficients δ and β by using mean values of only the three data points specified by the respondents. However, three data points did not provide an adequate statistical "anchor" for estimating market share. The projections for the technologies that are likely to be introduced after the year 2000 with models developed with three observations were poor. We therefore used interpolation to expand the number of data points to overcome this deficiency. Intermediate values developed through linear interpolation provided additional market penetration points for each survey respondent. We took the liberty of assuming that the respondents had a smooth market share transition in mind, and that imputation of values for intermediate years would be consistent with their thinking. The resulting data set had far more "observations," presumably reasonably accurately reflecting experts' opinions about intermediate year market penetrations. We used mean values for years 2000 through 2020 to obtain revised estimates of δ and β. Model coefficients were estimated by using the nonlinear regression procedure within the SHAZAM econometrics software (McGraw-Hill, 1993). Additional data points (18 per technology) within the expanded data set provided a fit for all models, which led to plausible results for all technologies. The results of the final model estimation (based on 21 data points) are summarized in Table 9. The t-statistics show that coefficient values are significant for each technology and the goodness of fit is high (to be expected from our assumptions), as shown by the R-square values.

Each model in Table 9 was estimated independent of others. When a number of market share models of this type are estimated independently, and then combined, the sum of market shares will exceed 100% at some point. This requires that the sum of market shares be normalized to 100%. We checked and found that the sum of projected market shares will require such an adjustment after 2026. As new technologies will penetrate the market, the conventional ICE share of the market will decline. Both conventional ICE and the combined total share for all new technologies would reach 50% market share at the same point in time 2033, if the projections were based only on the value of parameter δ for the conventional ICE. However, because the sum of individual model projections exceeded 100% by the year 2027, the 50% point in the normalized version (Fig. 1) was reached in 2030.

Figure 1 shows the predictions of the individual models, except for the conventional ICE. Symbols show the survey responses, and solid lines show the model projections. We applied the above estimated models to compute market shares for conventional ICE, EV, ICE HEV, gas turbine HEV, fuel cell HEV, and "other technologies." The values shown by solid lines in the figure are the normalized market shares for the new technologies.

Figure 1 does not show the share of conventional ICE vehicles. This technology's share is nearly 100% during the early years, while the highest share for any of the new technologies does not exceed 16%. The projected conventional ICE technology market share, which is not shown in Figure 1, is 50% of the new vehicle market in 2030. Therefore, the experts have considered that various superior attributes of the conventional technology will restrain the growth of the new technologies for a long time to come.

On the other hand, using the one standard market share model in the fashion used here, our results imply that electric drivetrain vehicles will begin to "take off" in the marketplace between 2020 and 2030. By 2040, when the projections are extended beyond that shown in Fig. 1, only 20% of new vehicles are conventional ICE. Extension of this growth would imply dominance of the marketplace by electric drivetrain vehicles in the second half of the 21st century. Figure 2 shows survey mean and statistically projected market shares for new technologies for the years 2000, 2010, 2020, and 2030. The number at the top of each bar represents the sum of new technology market shares. Subtracting each value from 100 percent provides conventional ICE market share estimates.

The market share analysis indicates that if the current research and development efforts are continued, EVs and ICE HEVs will penetrate the market first, at about the same time. ICE HEVs will penetrate at a slightly more rapid rate and would surpass EVs after 2010. Gas turbine and fuel-cell-powered vehicles are projected to start later, but they exhibit more rapid rates of penetration than EVs and ICE HEVs once they become technically and economically competitive. The fuel cell HEV is actually projected to have the most rapid rate of market penetration when it becomes technically and economically competitive. Other technologies are projected to have the smallest share of the market. An alternative version of the market share analysis has also been conducted based on median values of the responses but, is not included here for brevity. This alternative market share projection showed two highly noteworthy differences from the one presented here: (1) "other technologies" have zero market share and (2) fuel cell HEVs "take off" toward the middle of the century.

CONCLUSIONS

Detailed category-by-category findings have been summarized at the beginning of the paper and will not be summarized here. The broader implications of the predictions of the respondents to this survey are as follows:

(1) The PNGV goal 3 — tripling fuel economy of mid-sized vehicles, consistent with "constant dollar" life-cycle ownership cost that does not exceed the cost of today's mid-sized vehicle — will not be accomplished.

(2) The Energy Policy Act (EPACT) of 1992 goal of substituting 30% non-petroleum alternative and replacement fuels by 2010 (Santini et al., 1994) will not be accomplished by the introduction of electric drivetrain vehicles, even if those vehicles use electricity from the grid (nearly completely non-petroleum) to the maximum extent possible. Projections of new vehicle market share for the EVs and HEVs are far too low to meet the EPACT goal in this manner.

(3) Respondents to this survey are convinced that the purpose of introducing EVs and HEVs is to reduce emissions and that most HEVs will be designed to use electricity from the grid.

(4) Respondents to this survey are optimistic that battery storage technology consistent with most long-term goals of the U.S. Advanced Battery Consortium is possible. They also believe that future HEVs will have considerable all-electric range capability, providing the potential to use electricity rather than petroleum-based fuels for nearly all urban driving.

(5) Respondents to this survey also anticipate that, throughout the study period, petroleum-based fuels (gasoline, diesel, kerosene, and jet fuel) will be the dominant fuels for HEVs when powered by the HEV power unit. However, dependent upon assumptions external to the study, a very large amount of petroleum fuels could be displaced by electric power.

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Table 1: Organizational Breakdown of Respondents to the Second-Stage Delphi Questionnaire

Type of Organization	Number	Percentage
Industry		
Automotive OEM	21	22.5
Vehicle/Engine	5	5.4
Electric/Electronic	5	5.4
Battery	1	1.1
Others	12	12.9
Industry Sum	44	47.3
Government	13	14.0
Academics	9	9.7
Others	27	29.0

Table 2: Detailed Question Response Statistics for Vehicle Attributes

Electric Vehicle	Year	n	Mean	Mode	Median	Interquartile Values	optimist	pessimist
Range (km)	2000	92	179	150	150	250/150	220	138
	2010	92	270	250	250	350/200	341	199
	2020	92	358	250	350	450/250	465	250
Recharge time (mins.)	2000	92	233	300	300	120/300	160	307
	2010	91	141	120	120	30/300	64	217
	2020	92	85	120	45	30/120	22	148
Maintenance interval (1000s of km)	2000	90	20	15	15	30/10	31	10
	2010	88	34	30	30	32/15	46	21
	2020	88	48	30	50	75/30	67	29
0-50 kph (sec)	2000	90	7.4	7.0	7.0	7/9	6.0	8.8
	2010	90	5.8	5.0	5.0	5/7	4.4	7.2
	2020	89	5.2	5.0	5.0	4/5	4.0	6.3
Max. uphill grade (%)	2000	88	5.11	5.0	5.0	5/5	5.9	4.2
	2010	87	6.78	7.0	7.0	7/5	7.8	5.7
	2020	86	7.78	7.0	7.0	11/7	9.5	6.2

Hybrid Electric Vehicle	Year	n	Mean	Mode	Median	Interquartile Values	optimist	pessimist
Range (km)	2000	91	353	350	350	450/250	420	286
	2010	91	469	450	450	450/450	539	398
	2020	91	527	650	450	650/450	628	423
Recharge time (mins.)	2000							
	2010							
	2020							
Maintenance interval (1000s of km)	2000	87	17	15	15	15/14	24	10
	2010	86	28	30	30	30/15	38	18
	2020	87	38	30	30	50/28	53	23
0-50 kph (sec)	2000	90	6.9	7.0	7.0	5/7	5.7	8.2
	2010	89	5.5	5.0	5.0	5/7	4.3	6.6
	2020	90	4.7	5.0	5.0	3/5	3.6	5.8
Max. uphill grade (%)	2000	88	5.88	5.0	5.0	7/5	7.2	4.5
	2010	87	7.77	7.0	7.0	11/7	9.3	6.2
	2020	88	9.32	11.0	11.0	11/7	11.0	7.6

Table 3: Detailed Question Response Statistics for Vehicle Fuel Economy Ratios

Fuel Economy Ratio to 2000 Gasoline Vehicle	Year	n	Mean	Mode	Median	Interquartile Values	optimist	pessimist
Conventional ICE Vehicle	2000	83	1.00	1.0	1.0	1.0/1.0	1.00	1.00
	2010	79	1.09	1.1	1.1	1.2/0.9	1.23	0.94
	2020	79	1.16	1.2	1.2	1.3/0.8	1.44	0.87
Electric Vehicle	2000	63	1.41	1.0	1.0	1.5/0.8	2.03	0.77
	2010	63	1.54	1.0	1.0	1.5/0.8	2.30	0.76
	2020	63	1.67	1.0	1.0	1.5/0.75	2.58	0.72
ICE Hybrid Vehicle	2000	64	1.18	1.1	1.1	1.3/0.8	1.55	0.81
	2010	65	1.29	0.8	1.1	1.5/0.8	1.81	0.75
	2020	65	1.40	0.5	1.2	1.7/0.7	2.08	0.69
Gas Turbine Hybrid	2000	60	1.22	1.2	1.2	1.5/0.9	1.59	0.86
	2010	62	1.40	1.0	1.15	1.7/0.84	1.95	0.84
	2020	62	1.52	1.5	1.2	1.7/0.8	2.24	0.81
Fuel Cell Hybrid	2000	53	1.27	2.0	1.1	1.75/0.7	1.85	0.67
	2010	57	1.42	1.5	1.2	1.9/0.7	2.14	0.66
	2020	58	1.59	1.0	1.2	2.0/0.6	2.53	0.65

Table 4: Detailed Question Response Statistics for Vehicle Cost Ratios

Cost Ratio to 1993 Gasoline Vehicle	Year	n	Mean	Mode	Median	Interquartile Values	optimist	pessimist
Conventional ICE Vehicle	2000	87	1.26	1.2	1.2	1.1/1.3	1.13	1.38
	2010	86	1.60	1.4	1.5	1.4/1.8	1.33	1.88
	2020	87	2.02	2.0	2.0	1.55/2.3	1.53	2.51
Electric Vehicle	2000	87	2.29	2.0	2.0	2.0/2.6	1.78	2.78
	2010	86	2.31	2.0	2.2	2.0/2.5	1.85	2.76
	2020	87	2.38	2.0	2.2	2.0/2.5	1.81	2.94
ICE Hybrid Vehicle	2000	85	2.47	2.2	2.4	2.0/2.9	1.87	3.06
	2010	84	2.44	2.5	2.4	2.0/2.6	1.87	3.00
	2020	85	2.54	2.5	2.5	2.0/2.8	1.89	3.17
Gas Turbine Hybrid	2000	76	3.27	3.0	3.0	2.5/4.0	2.33	4.22
	2010	84	3.04	3.0	3.0	2.3/3.1	2.26	3.83
	2020	85	3.07	3.0	3.0	2.3/3.3	2.21	3.90
Fuel Cell Hybrid	2000	70	5.15	4.0	4.5	3.0/6.0	3.13	7.16
	2010	81	4.36	6.0	4.0	3.0/6.0	2.91	5.77
	2020	83	3.98	4.0	3.8	2.5/5.0	2.53	5.40

Table 5: Detailed Question Response Statistics for HEV Fuel Types

	HEV/ICE			HEV/Turbine			HEV/Fuel Cell		
Fuel Type	2000	2010	2020	2000	2010	2020	2000	2010	2020
Alcohols	1	3	3	2	2	2	15	18	16
Natural Gas		9	10	13	18	16	11	13	9
Diesel	5	8	6	6	7	7			
Gasoline	57	42	40	13	10	10	2	2	2
Jet Fuel/Kerosene				20	20	19			1
Hydrogen			1	1	1	2	22	22	27
Others	1	1	3			2	1	1	3
No. of Responses	64	63	63	55	58	58	51	56	58

Table 6: Detailed Question Response Statistics for Market Share Estimates

New LDV Market Share Estimate (%)	Year	n	Mean	Mode	Median	Interquartile Values	optimist	pessimist
Conventional ICE Vehicle	2000	89	97.12	99	98	99/95	99.24	94.95
	2010	88	89.71	90	90	96/87	95.93	83.47
	2020	89	77.55	80	80	90/70	89.35	65.59
Electric Vehicle	2000	89	1.31	1	1	2/0.5	2.09	0.51
	2010	88	4.10	1	4	5/1	6.59	1.61
	2020	89	7.49	10	6	10/2	12.00	2.90
ICE Hybrid Vehicle	2000	89	1.14	0	0.2	1/0	2.24	0.01
	2010	88	4.09	1	2	5/1	7.24	0.94
	2020	89	7.91	4	5	10/2	13.41	2.30
Gas Turbine Hybrid	2000	89	0.16	0	0	0/0	0.32	0.00
	2010	88	0.93	0	0	1/0	1.87	0.00
	2020	89	2.96	0	1	4/0	5.68	0.18
Fuel Cell Hybrid	2000	89	0.16	0	0	0/0	0.32	0.00
	2010	88	0.71	0	0	0.7/0	1.42	0.00
	2020	89	2.96	0	1	4/0	5.71	0.15

Table 7: Detailed Question Response Statistics for Battery Attributes

		Specific Energy			Specific Power			Life (cycles)			Initial Cost		
Battery	year	n	median	quartiles	n	median	quartiles	n	median	quartiles	n	median	quartiles
Lead acid	2000	55	40	35/40	54	130	100/200	55	600	500/700	54	190	150/200
	2010	55	44	40/50	53	160	110/200	53	700	530/800	54	180	150/200
	2020	54	45	40/51	54	190	120/200	53	800	600/1000	53	180	150/200
Li polymer	2000	39	100	100/120	38	140	120/150	36	500	500/600	36	700	200/800
	2010	41	150	130/150	39	160	150/180	37	750	700/900	37	400	150/500
	2020	41	170	145/200	39	180	180/200	37	1000	900/1050	37	250	125/500
NiCd	2000	45	57	55/60	43	180	175/200	42	1000	1000/1300	43	600	500/600
	2010	44	60	55/65	43	190	175/210	41	1300	1000/1500	43	500	400/600
	2020	43	62	55/66	43	200	180/220	41	1500	1000/1800	42	450	400/600
NiMH	2000	43	75	70/75	41	155	150/175	41	1000	500/1000	43	583	350/600
	2010	43	80	80/85	41	180	150/200	41	1100	550/1331	43	400	200/500
	2020	42	85	85/95	41	200	175/220	40	1250	600/1500	42	300	180/450
NaS	2000	41	90	80/110	40	142	130/150	40	700	500/800	41	400	250/450
	2010	40	100	90/110	40	150	140/160	39	850	500/1000	41	360	200/400
	2020	39	110	90/110	40	150	150/170	38	1000	600/1100	40	333	150/400

Table 8: Detailed Question Response Statistics for Motor Cost Estimates

Cost Ratio to 1993 Direct Current Motor	Year	n	Mean	Mode	Median	Interquartile Values	optimist	pessimist
Direct Current	2000	47	1.17	1.0	1.2	1.0/1.2	1.02	1.32
	2010	46	1.32	1.0	1.2	1.0/1.4	1.06	1.58
	2020	45	1.45	1.0	1.3	1.0/1.6	1.04	1.85
AC Induction	2000	47	1.74	1.5	1.5	1.0/2.0	1.17	2.30
	2010	46	1.50	1.5	1.5	1.1/1.7	1.12	1.88
	2020	45	1.42	1.2	1.3	1.1/1.7	1.05	1.78
DC Brushless	2000	46	2.45	2.0	2.0	1.5/2.5	1.67	3.23
	2010	45	1.99	2.0	1.8	1.4/2.0	1.40	2.56
	2020	44	1.68	1.5	1.5	1.1/2.0	1.16	2.19

Table 9: Results of Model Coefficient Estimation

Technology	δ	β	R-Square
Conventional ICE	33.1 (81.6)[a]	-10.2 (-44.9)	0.99
Electric Vehicle	53.7 (42.8)	13.3 (30.8)	0.98
ICE HEV	50.4 (43.3)	12.3 (30.3)	0.98
Gas Turbine HEV	50.6 (48.2)	8.7 (31.7)	0.99
Fuel Cell HEV	47.5 (50.4)	7.7 (32.1)	0.99
Other Technologies	66.9 (44.8)	10.4 (33.9)	0.99

[a] Numbers in parenthesis show t-statistics.

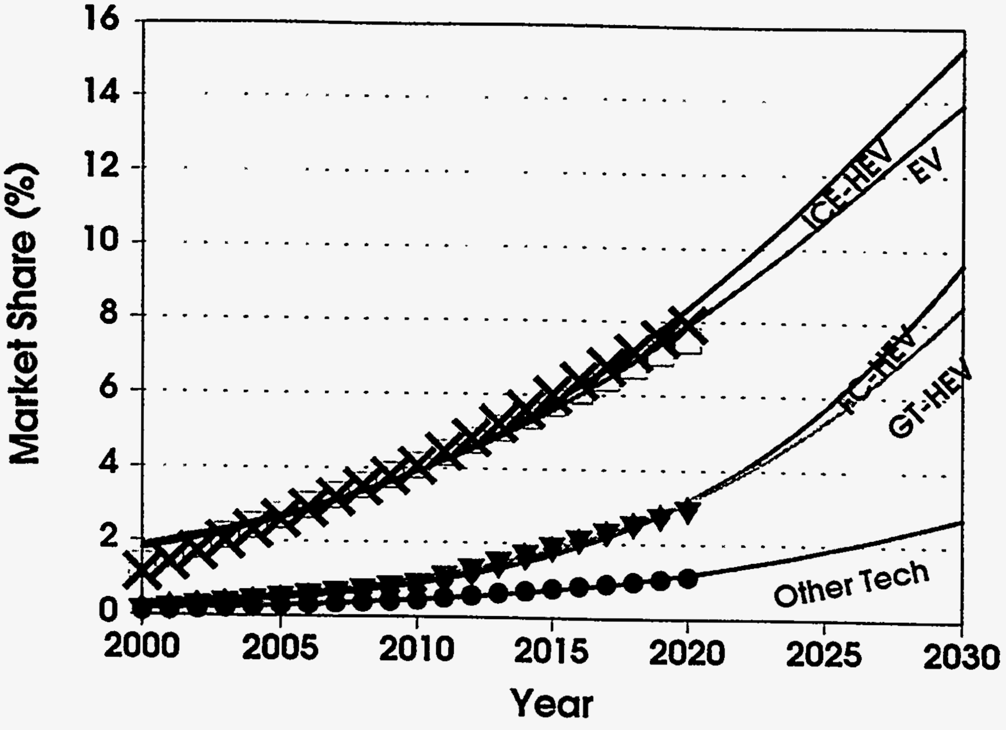

Figure 1: Application of Market Penetration Models for New Technologies

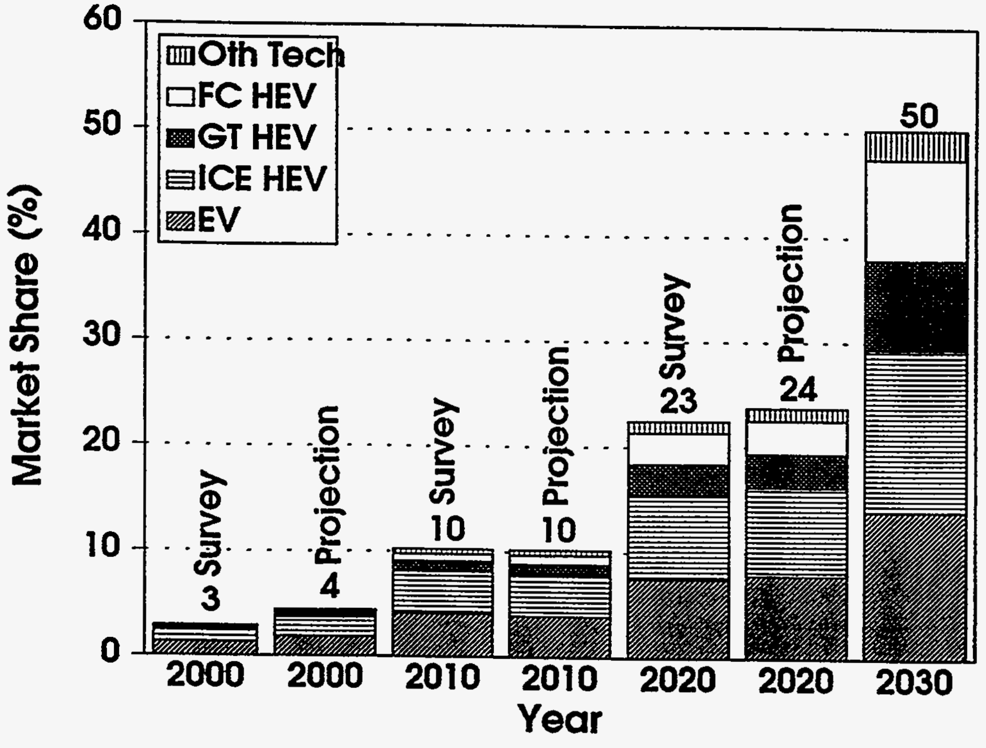

Figure 2: New Technology Market Shares in 2000, 2010, 2020, and 2030