Batteries for Electric Drive Vehicles: Evaluation of Future Characteristics and Costs through a Delphi Study

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ABSTRACT

Uncertainty about future costs and operating attributes of electric drive vehicles (EVs and HEVs) has contributed to considerable debate regarding the market viability of such vehicles. One way to deal with such uncertainty, common to most emerging technologies, is to pool the judgments of experts in the field. Data from a two-stage Delphi study are used to project the future costs and operating characteristics of electric drive vehicles. The experts projected basic vehicle characteristics for EVs and HEVs for the period 2000-2020. They projected the mean EV range at 179 km in 2000, 270 km in 2010, and 358 km in 2020. The mean HEV range on battery power was projected as 145 km in 2000, 212 km in 2010, and 244 km in 2020. Experts' opinions on 10 battery technologies are analyzed and characteristics of initial battery packs for the mean power requirements are presented. A procedure to compute the cost of replacement battery packs is described, and the resulting replacement costs are presented. Projected vehicle purchase prices and fuel and maintenance costs are also presented. The vehicle purchase price and curb weight predictions would be difficult to achieve with the mean battery characteristics. With the battery replacement costs added to the fuel and maintenance costs, the conventional ICE vehicle is projected to have a clear advantage over electric drive vehicles through the projection period.

INTRODUCTION

As a part of the government's efforts to support research that reduces petroleum consumption, the Office of Transportation Technologies (OTT) within the U.S. Department of Energy (DOE) funds programs leading to increased vehicle fuel economy and use of alternative fuels. A secondary goal is the development of technologies that are less harmful to the environment, as required by legislation and stricter vehicular emission standards. Some of the OTT-funded research provides an impetus to the development of technologies that can improve air quality, particularly in large urban areas, and also alleviate concerns related to global warming associated with burning of fossil fuels. Air quality in the nation's urban areas has been slowly improving, but attainment of standards has proven especially difficult in some urban areas. To some degree, there is concern about diminished air quality in major urban areas in the future due to growth in vehicle use. Federal and state governments therefore continue to develop regulations providing for even stricter vehicle emission standards. The states with the worst problems have contemplated regulations requiring vehicles with zero and *ultra-low* tailpipe emissions. As a consequence of these developments, OTT has funded research to develop such vehicles, which are mandated by some states.

Electric and hybrid electric vehicles are viewed as solutions to the urban air quality problem of tropospheric (near-ground) ozone. They are also being considered for the purpose of reducing combustion particulates, the damage from which is suspected by some to exceed that from ozone. Because they will use energy stored in batteries or other storage devices, such as ultra-capacitors and flywheels, electric vehicles (EVs) have no tailpipe emissions and are classified as zero emissions vehicles (ZEVs). While EVs have the potential to reduce emissions of pollutants that are precursors to ozone, the technology is unproven, expensive, and can benefit greatly from research and development. Current batteries, EVs' most viable energy storage system, are expensive and bulky, have short cycle life, and also have low energy storage capacity, resulting in limited vehicle range. Advanced battery technologies require extensive research and development efforts, which are being conducted under the auspices of the U.S. Advanced Battery Consortium (USABC). Candidate hybrid electric vehicles (HEVs), which are less developed than EVs, are anticipated to use both electrical energy from batteries and power from an onboard system consisting of a gas turbine (GT), an internal combustion engine (ICE), or a fuel cell (FC). An HEV can be a range extender, first using the battery power until it is exhausted and then switching to a power unit for the remainder of the trip. Among HEVs, range extenders usually have the smallest power units. In an alternative configuration, an HEV is powered by a power unit with considerably less power than a conventional vehicle, and peak power is supplied from power stored in the batteries. In this configuration, batteries are charged when the pattern of driving requires less power than what the power unit can provide and through regenerative braking. This is far more beneficial to overall energy use when driving includes many stops and starts. An HEV has the potential to significantly increase the vehicle fuel economy and thereby reduce petroleum consumption and greenhouse gas emissions. However, its two energy storage and power systems make it complex and expensive.

EV and HEV research and development are conducted with public and private funds. Publication of private-sector research and some public-sector research, conducted under agreements that results will remain proprietary, has tended to provide only limited and sketchy details. Battery research has attracted considerable attention because the EV's limited range is viewed as the major barrier to its market viability. However, published information is limited. The battery is also a significant component of EV and HEV costs. Research on electric drive systems that will benefit both the EV and HEV has been under way for some time in both the public and private sectors. Although vehicle manufacturers have not mass-produced either an EV or an HEV, they have recently shown some willingness, due to intense regulatory pressure, to market them in the future. Since comprehensive information on EV and HEV technologies is not readily available, DOE and OTT have sought ways to acquire such information.

In order to obtain a better understanding of the state of both EV and HEV technologies, OTT sponsored a two-stage Delphi study. Argonne National Laboratory (ANL) conducted this study, with assistance from the Society of Automotive Engineers (SAE) Cooperative Research Program (CRP). The goal of the study was to collect information on vehicle attributes and components, evaluate their performance, and assess their market-penetration potential. The first step was to survey the experts in the field and solicit their opinions. The results of the study will help decision makers to properly orient their research and development efforts.

Information regarding study methodology and questionnaire development has been published earlier [Ng, Anderson, and Santini, 1995; Ng et al., 1996]. In all, 93 valid second-stage responses were available for analysis. Industry was the largest responding group, providing 47% of the responses. Within the industry group, original equipment manufacturers provided nearly half the responses (23% of the total). Private research organizations and potential component suppliers provided 29% of the responses, and government and academic institutions provided the remainder.

This paper presents an analysis of vehicle attributes and battery technology data from the Delphi study. Ten battery technologies are evaluated, and battery replacement costs for EVs and HEVs are presented. Characteristics of EVs and HEVs that emerged from this analysis are summarized. The vehicle and battery characteristics presented here are taken from the survey; the authors have not attempted to develop any vehicle or battery specifications.

ELECTRIC DRIVE VEHICLE CHARACTERISTICS

The survey was designed to collect information for the years 2000, 2010, and 2020. The questionnaire contained sections on vehicles, components, and system impacts. Each section contained questions seeking opinions on critical characteristics of EVs and HEVs. Some questions within the vehicles section sought experts' opinions on such vehicle attributes as range, acceleration, highest acceptable uphill grade, seating capacity, cargo capacity, curb weight, power, battery recharging time, and maintenance interval. For the HEV, an additional question was asked concerning the engine range. We computed the implied battery-only range by subtracting engine range from the total HEV range. Experts also provided opinions on EV and HEV price, fuel and maintenance cost, and fuel economy. Within the components section of the questionnaire, they responded to questions about 10 battery technologies. We analyzed the responses to all these questions to arrive at two separate estimates of EV and HEV characteristics, primary (i.e., resulting from respondents' vehicle opinions) and secondary (i.e., resulting from respondents' battery opinions).

For most of the analysis presented here, we have used mean values of the responses. We have listed several other values, such as number of valid responses, median, and mode, whenever we summarize the responses in a table. We also present *optimistic* and *pessimistic* values for the basic vehicle characteristics. These values represent means of the responses either below and at the median point or above the median point (i.e., the responses are split into two groups at the median point). A group's *optimistic* or *pessimistic* identity is dependent on the attribute. For example, because longer range and lower vehicle curb weight are desirable, the *optimistic* group for range will be above the median and the *optimistic* group for curb weight will be at and below the median. A good measure of the level of agreement among the respondents is the interquartile range. A narrower interquartile range represents a higher degree of agreement. We also present these statistics for the data summarized in tables.

BASIC VEHICLE CHARACTERISTICS — The basic vehicle characteristics for EVs and HEVs are power, curb weight, seating capacity, cargo capacity, and range. These characteristics are summarized in Table 1. Since events subsequent to initiation of the study appear to have pushed back the likely introduction date for EVs past 2000, the table contains values for the year 2005, which we derived through linear interpolation. As can be seen from the number of observations, most respondents answered the basic vehicle characteristics questions. They project consistent improvements in both the EV and the HEV. Other characteristics on which opinions were requested but are not summarized in Table 1 include acceleration, recharging time, and maintenance interval [Ng et al., 1996]. Such attributes as acceleration, top speed, and the ability to negotiate a reasonable uphill grade are dependent on vehicle design and power. Responses to recharging time and maintenance interval queries are summarized in a separate publication [ANL, 1996].

The mean EV range is 179 km in the year 2000, increasing to 270 km by 2010 (a 51% increase) and to 358 km by 2020 (a 100% increase). The mean EV power is 66.7 kW in the year 2000, 86.1 kW in 2010 (a 29% increase), and 99.2 kW in 2020 (a 49% increase over 2000). The respondents appear to have recognized that most batteries would have to improve less to provide the needed power, compared to the extent of improvements needed in specific energy to obtain the desired range. Experts appear to have provided the peak power rating for the motor, rather than the continuous power rating, and did not seem to foresee substantial improvements in EV power between now and 2000. At present, a typical AC induction motor is rated at approximately 66 kW peak power, and a DC motor, around 52 kW [Cuenca and Gaines, 1996].

An EV is projected to have a mean curb weight of 1,538 kg in 2000, 1,351 kg in 2010 (a 12% reduction), and 1,222 kg in 2020 (a 21% reduction). A mid-size conventional car had a curb weight of 1,368 kg in 1993. While its curb weight in 2010 is comparable with that of today's conventional mid-size car, the future EV is not likely to have the same seating capacity. A present mid-size conventional car's seating capacity is 5, but the mean seating capacity of an EV is projected at 3 or 4 until 2010. The projected improvements in power, range, and curb weight pose substantial challenges to EV manufacturers. Lightweight materials, such as aluminum and carbon polymer, have the potential to reduce the curb weight, but vehicles that use such materials will cost more. An aluminum-intensive mid-size conventional car would weigh 31% less when power per unit mass is held constant; however, such a car would cost $1,200 (1990 dollars) more [Stodolsky, Vyas, and Cuenca, 1995].

Table 1 also shows the projected attributes of an HEV. Its mean power is projected at 79.6 kW in 2000, 99.1 kW in 2010 (a 24% increase), and 108.6 kW in 2020 (a 36% increase). Three HEV range values are summarized in the table: (1) total, (2) engine, and (3) battery; respondents provided "total" and "engine" ranges, and we computed the "battery" range for each respondent. A large majority (94%) of the respondents expected the future HEV to be a "range extender." A small battery range indicates that the respondent did not expect the HEV to be a "range extender" because it will not be charged through the electric grid. Only 7 respondents in the year 2000 and 5 respondents each in 2010 and 2020 provided very small battery ranges.

The mean total range of an HEV is projected to be 353 km in 2000, 469 km in 2010 (a 33% increase), and 527 km in 2020 (a 49% increase). The total range is less than the range of a conventional vehicle (500-550 km) until 2020, which indicates that the respondents did not see HEVs being used for vacations and long trips until after 2010. The mean engine range is 215 km in 2000, 257 km in 2010 (a 20% increase), and 281 km in 2020 (a 31% increase). The engine range does not increase as much as the total range. The respondents saw the battery supplying more of the HEV range, increasing from 39% of the total range in 2000 to 47% in 2020.

The mean curb weight of an HEV is 1,556 kg in 2000, 1,382 kg in 2010 (a 11% reduction), and 1,265 kg in 2020 (a 19% reduction). The rate of weight reduction is slightly lower than the rate for an EV (see above). The respondents saw an HEV as being slightly heavier than an EV and having one additional seat through 2010.

VEHICLE COSTS — Respondents were asked to provide EV and HEV purchase prices and fuel and maintenance costs relative to the 1993 conventional vehicle. Vehicle purchase prices are summarized in Table 2, and fuel and maintenance costs are summarized in Table 3. The respondents projected the conventional vehicle to cost 26% more by 2000, 60% more by 2010, and 102% more by 2020. They expected both EVs and HEVs to cost more than the conventional vehicle through the year 2020. An EV is projected to cost 129% more than the 1993 conventional vehicle in the year 2000, 131% more in 2010, and 138% more in 2020. The least expensive HEV, an ICE-powered version, will cost 147% more than the 1993 conventional vehicle in 2000, 144% more in 2010, and 154% more in 2020. A fuel-cell HEV is projected to be the most expensive of the four electric drive vehicles, costing 415% more than the 1993 conventional vehicle in 2000 and 298% more in 2020. The interquartile ranges are wider for the gas-turbine-powered and fuel-cell-powered HEVs.

TABLE 1 EV and HEV Basic Vehicle Characteristics

Attribute	Year	Obs	Mean	Mode	Median	Qrtl-1	Qrtl-3	Optimist	Pessimist
Electric Vehicle									
Range (km)	2000	92	179	150	150	150	250	220	138
	2005	92	225	200	200	194	300	281	169
	2010	92	270	250	250	238	350	341	199
	2020	92	358	250	350	250	450	465	250
Seats	2000	91	3	4	4	2	4	4	3
	2005	91	4	4	4	3	4	4	3
	2010	91	4	4	4	4	4	5	4
	2020	90	5	5	5	4	5	5	4
Curb weight (kg)	2000	88	1,538	1,800	1,400	1,400	1,800	1,305	1,771
	2005	88	1,444	1,600	1,400	1,300	1,600	1,240	1,649
	2010	88	1,351	1,400	1,400	1,200	1,400	1,175	1,527
	2020	88	1,222	1,200	1,200	1,200	1,400	1,075	1,370
Power (kW)	2000	91	66.7	70.0	70.0	50.0	70.0	79	54
	2005	91	76.4	80.0	80.0	60.0	80.0	90	63
	2010	91	86.1	90.0	90.0	70.0	90.0	100	72
	2020	90	99.2	110.0	99.8	90.0	110.0	114	84
Hybrid Electric Vehicle									
Total range (km)	2000	91	353	350	350	250	450	420	286
	2005	91	411	400	400	350	450	480	342
	2010	91	469	450	450	450	450	539	398
	2020	91	527	650	450	450	650	628	423
Engine range (km)	2000	88	215	300	200	150	300	286	144
	2005	88	236	300	204	175	300	309	164
	2010	88	257	300	209	200	300	331	183
	2020	88	281	300	300	200	300	345	218
Battery range (km)	2000	88	145	150	150	100	200	199	90
	2005	88	178	200	178	125	225	246	110
	2010	88	212	250	205	150	250	293	130
	2020	88	244	350	250	150	350	357	152
Seats	2000	89	4	4	4	4	4	4	3
	2005	90	4	4	4	4	5	5	4
	2010	88	5	4	4	4	5	5	4
	2020	89	5	5	5	4	6	6	5
Curb weight (kg)	2000	85	1,556	1,800	1,400	1,400	1,800	1,338	1,769
	2005	84	1,469	1,600	1,400	1,300	1,600	1,277	1,659
	2010	84	1,382	1,400	1,400	1,200	1,400	1,215	1,548
	2020	85	1,265	1,200	1,200	1,200	1,400	1,112	1,415
Power (kW)	2000	87	79.6	70.0	70.0	70.0	90.0	94	65
	2005	86	89.4	80.0	80.0	80.0	100.0	104	75
	2010	86	99.1	90.0	90.0	90.0	110.0	113	85
	2020	87	108.6	110.0	110.0	90.0	110.0	124	94

[a] The statistics for EV and HEV range have been published earlier (see Ng et al., 1996).

TABLE 2 Vehicle Purchase Price (in nominal dollars) for Conventional and Electric Drive Vehicles

Vehicle Technology	Year	Obs	Mean	Mode	Median	Quartile-1	Quartile-3	Optimist	Pessimist
Conventional ICE	2000	87	18,862	18,000	18,000	16,500	19,650	16,929	20,751
	2005	86	21,457	19,500	20,250	18,750	23,325	18,454	24,434
	2010	86	24,052	21,000	22,500	21,000	27,000	19,978	28,727
	2020	87	30,336	30,000	30,000	23,250	34,500	22,919	37,585
Electric vehicle	2000	87	34,300	30,000	30,000	30,000	40,500	26,724	41,703
	2005	86	34,447	30,000	31,500	30,000	39,000	27,246	41,562
	2010	86	34,594	30,000	33,000	30,000	37,500	27,767	41,421
	2020	87	35,703	30,000	33,000	30,000	37,500	27,181	44,032
ICE-powered hybrid	2000	85	37,082	33,000	35,250	30,000	43,500	28,025	45,928
	2005	84	36,817	35,250	35,625	30,000	41,663	28,070	45,459
	2010	84	36,552	37,500	36,000	30,000	39,825	28,114	44,989
	2020	85	38,051	37,500	37,500	30,000	42,000	28,339	47,536
Gas-turbine-powered hybrid	2000	76	49,089	45,000	45,000	37,500	60,000	34,903	63,276
	2005	76	47,372	45,000	45,000	37,181	53,344	34,385	60,360
	2010	84	45,655	45,000	45,000	36,863	46,688	33,808	57,443
	2020	85	46,016	45,000	45,000	36,000	48,750	33,207	58,528
Fuel-cell-powered hybrid	2000	70	77,231	60,000	67,500	46,125	86,250	47,023	107,439
	2005	70	71,288	75,000	63,750	45,563	88,125	45,344	96,967
	2010	81	65,344	90,000	60,000	45,000	90,000	43,665	86,495
	2020	83	59,770	60,000	57,000	37,500	75,000	37,968	81,054

TABLE 3 Fuel and Maintenance Costs (nominal cents per km) for Conventional and Electric Drive Vehicles [a]

Vehicle Technology	Year	Obs	Mean	Mode	Median	Quartile-1	Quartile-3	Optimist	Pessimist
Conventional ICE	2000	85	6.9	6.4	6.9	6.4	7.5	6.3	7.5
	2005	84	7.7	7.2	7.5	6.9	8.4	6.8	8.7
	2010	84	8.5	8.1	8.1	7.5	9.2	7.2	9.8
	2020	83	10.4	8.7	9.2	8.4	11.6	7.9	12.9
Electric vehicle	2000	84	8.2	7.5	7.5	6.4	8.7	6.1	10.3
	2005	83	8.2	7.2	7.5	6.6	8.7	6.2	10.3
	2010	83	8.3	6.9	7.5	6.9	8.7	6.2	10.4
	2020	83	8.9	8.7	7.5	6.2	10.4	5.8	11.9
ICE-powered hybrid	2000	79	9.0	8.7	8.7	7.5	9.8	7.3	10.7
	2005	79	9.2	8.4	8.7	7.8	10.1	7.4	11.1
	2010	79	9.4	8.1	8.7	8.1	10.4	7.5	11.4
	2020	79	10.9	11.0	10.4	8.4	11.6	8.1	13.7
Gas-turbine-powered hybrid	2000	79	11.6	8.7	10.4	8.7	11.6	8.5	14.6
	2005	79	11.4	9.5	10.4	8.7	11.6	8.6	14.3
	2010	80	11.3	10.4	10.4	8.7	11.6	8.6	14.1
	2020	80	12.0	10.4	10.4	8.7	12.7	8.9	15.3
Fuel-cell-powered hybrid	2000	73	15.4	11.6	12.1	11.6	17.3	9.8	21.0
	2005	73	14.3	11.6	11.8	10.7	15.9	9.7	18.8
	2010	76	13.1	11.6	11.6	9.8	14.4	9.7	16.6
	2020	77	13.6	11.6	11.6	9.8	14.4	9.1	18.0

[a] Excludes battery replacement costs for electric drive vehicles.

TABLE 4 Specific Energy (in Wh/kg) for 10 Battery Technologies

Battery Technology	Year	Obs	Mean	Mode	Median	Quartile-1	Quartile-3
Lead acid	2000	55	40	40	40	35	40
	2005	55	42	40	42	38	45
	2010	55	44	40	44	40	50
	2020	54	48	45	45	41	51
Lithium iron disulfide	2000	24	97	100	96	80	100
	2005	22	106	105	104	91	109
	2010	23	116	110	110	100	130
	2020	32	138	150	135	119	150
Lithium polymer	2000	39	110	100	100	100	123
	2005	39	125	125	125	118	135
	2010	41	144	150	150	130	150
	2020	41	172	200	170	150	200
Nickel cadmium	2000	45	57	55	57	55	60
	2005	44	58	55	58	55	63
	2010	44	60	55	60	55	65
	2020	43	62	55	62	55	66
Nickel iron	2000	23	51	50	50	50	55
	2005	22	53	53	53	52	56
	2010	22	55	55	55	53	58
	2020	22	58	60	58	55	60
Nickel metal hydride	2000	43	73	75	75	70	75
	2005	43	78	78	78	74	81
	2010	43	83	80	80	80	85
	2020	42	89	85	85	85	95
Nickel zinc	2000	20	61	60	60	55	63
	2005	20	64	63	64	59	67
	2010	20	68	70	70	64	70
	2020	20	74	80	76	67	80
Sodium sulfur	2000	41	95	80	90	80	110
	2005	40	99	110	95	85	110
	2010	40	102	110	100	90	110
	2020	39	107	110	110	95	110
Zinc air	2000	29	116	120	120	100	120
	2005	28	127	125	125	110	135
	2010	28	137	150	130	120	150
	2020	27	146	150	150	130	160
Zinc bromide	2000	21	69	70	70	65	70
	2005	21	72	73	71	67	74
	2010	21	75	70	72	70	75
	2020	21	79	80	77	72	80

TABLE 5 Specific Power (in W/kg) for 10 Battery Technologies

Battery Technology	Year	Obs	Mean	Mode	Median	Quartile-1	Quartile-3
Lead acid	2000	54	155	200	130	100	200
	2005	53	173	200	145	110	200
	2010	53	190	200	160	120	200
	2020	54	214	200	190	120	200
Lithium iron disulfide	2000	22	167	150	155	150	195
	2005	22	188	225	178	159	215
	2010	23	209	300	200	168	235
	2020	32	269	350	235	200	350
Lithium polymer	2000	38	136	150	140	120	150
	2005	38	152	155	150	135	167
	2010	39	167	160	160	150	184
	2020	39	193	180	180	180	209
Nickel cadmium	2000	43	189	175	180	175	200
	2005	43	194	175	185	175	205
	2010	43	199	175	190	175	210
	2020	43	209	175	200	182	222
Nickel iron	2000	22	125	130	130	120	131
	2005	22	133	133	133	125	136
	2010	22	140	135	135	130	140
	2020	22	152	150	150	140	150
Nickel metal hydride	2000	41	165	150	155	150	175
	2005	41	174	150	168	150	188
	2010	41	184	150	180	150	200
	2020	41	203	200	200	175	220
Nickel zinc	2000	20	171	150	161	150	175
	2005	20	181	165	171	163	188
	2010	20	192	180	180	175	200
	2020	20	214	200	200	198	231
Sodium sulfur	2000	40	144	150	142	132	150
	2005	40	149	150	146	140	155
	2010	40	153	150	150	148	160
	2020	40	160	150	150	150	170
Zinc air	2000	27	91	100	100	83	100
	2005	27	100	100	105	91	110
	2010	27	108	100	110	100	120
	2020	26	122	120	120	113	130
Zinc bromide	2000	21	94	90	90	90	100
	2005	20	102	90	100	92	112
	2010	20	110	90	110	94	124
	2020	21	124	140	130	110	140

TABLE 6 Shelf Life (in years) for 10 Battery Technologies

Battery Technology	Year	Obs	Mean	Mode	Median	Quartile-1	Quartile-3
Lead acid	2000	50	3.4	3.0	3.0	3.0	4.0
	2005	49	3.9	3.5	3.5	3.0	4.3
	2010	49	4.4	4.0	4.0	3.0	4.6
	2020	49	4.4	5.0	4.5	3.0	5.0
Lithium iron disulfide	2000	21	3.5	4.0	4.0	3.0	4.0
	2005	21	4.0	4.5	4.5	3.5	4.5
	2010	21	4.6	5.0	5.0	4.0	5.0
	2020	29	5.7	5.0	5.0	5.0	6.0
Lithium polymer	2000	35	4.8	5.0	5.0	4.0	5.0
	2005	35	6.0	7.5	5.5	4.5	7.5
	2010	35	7.2	10.0	6.0	5.0	10.0
	2020	35	8.2	10.0	7.4	6.0	10.0
Nickel cadmium	2000	38	5.7	5.0	5.0	5.0	5.9
	2005	37	6.2	5.0	5.5	5.0	6.3
	2010	37	6.6	5.0	6.0	5.0	6.6
	2020	37	7.8	10.0	7.0	6.0	10.0
Nickel iron	2000	21	8.3	10.0	9.0	6.0	10.0
	2005	21	8.7	9.5	9.3	6.5	10.3
	2010	21	9.1	9.0	9.5	7.0	10.5
	2020	21	9.8	10.0	10.0	8.0	10.9
Nickel metal hydride	2000	37	4.6	5.0	4.7	3.0	5.0
	2005	37	5.3	5.5	4.9	3.9	5.5
	2010	37	6.0	6.0	5.0	4.7	6.0
	2020	36	6.7	5.0	6.0	5.0	7.0
Nickel zinc	2000	20	3.1	3.0	3.0	3.0	3.0
	2005	20	3.6	3.0	3.5	3.0	3.8
	2010	20	4.2	3.0	4.0	3.0	4.6
	2020	20	4.8	5.0	4.5	4.0	5.0
Sodium sulfur	2000	39	4.2	5.0	4.0	4.0	5.0
	2005	38	4.8	5.0	4.5	4.3	5.0
	2010	38	5.4	5.0	5.0	4.6	5.0
	2020	38	5.3	5.0	5.0	5.0	5.5
Zinc air	2000	24	3.8	3.0	3.0	3.0	4.0
	2005	24	4.3	3.5	3.5	3.5	4.2
	2010	24	4.9	4.0	4.0	4.0	4.4
	2020	24	5.3	5.0	4.5	4.0	5.0
Zinc bromide	2000	20	3.2	3.0	3.0	3.0	3.4
	2005	19	3.7	3.5	3.5	3.5	4.2
	2010	19	4.2	4.0	4.0	4.0	4.9
	2020	20	5.0	5.0	5.0	4.8	5.1

TABLE 7 Life (in Charge/Discharge Cycles) for 10 Battery Technologies

Battery Technology	Year	Obs	Mean	Mode	Median	Quartile-1	Quartile-3
Lead acid	2000	55	611	600	600	500	700
	2005	53	675	650	650	525	750
	2010	53	740	700	700	550	800
	2020	53	872	800	800	600	1,000
Lithium iron disulfide	2000	21	512	500	500	400	600
	2005	21	605	650	613	500	700
	2010	22	698	800	725	600	800
	2020	31	884	1,000	1,000	800	1,000
Lithium polymer	2000	36	577	500	500	500	600
	2005	36	726	600	625	600	750
	2010	37	876	700	750	700	900
	2020	37	1,185	1,000	1,000	900	1,050
Nickel cadmium	2000	42	1,255	1,000	1,000	1,000	1,300
	2005	41	1,341	1,000	1,150	1,000	1,400
	2010	41	1,428	1,000	1,300	1,000	1,500
	2020	41	1,546	1,000	1,500	1,000	1,800
Nickel iron	2000	21	1,055	1,000	1,000	1,000	1,127
	2005	21	1,174	1,050	1,100	1,025	1,305
	2010	21	1,294	1,100	1,200	1,050	1,482
	2020	21	1,545	1,200	1,350	1,200	1,848
Nickel metal hydride	2000	41	969	1,000	1,000	500	1,000
	2005	41	1,073	750	1,050	550	1,166
	2010	41	1,177	500	1,100	600	1,331
	2020	40	1,312	500	1,250	750	1,506
Nickel zinc	2000	20	427	400	400	375	463
	2005	20	498	450	463	431	533
	2010	20	570	500	525	488	603
	2020	20	716	600	650	575	825
Sodium sulfur	2000	40	683	500	700	500	800
	2005	39	756	750	775	550	900
	2010	39	829	1,000	850	600	1,000
	2020	38	910	1,000	1,000	625	1,075
Zinc air	2000	26	428	350	350	213	395
	2005	25	498	375	400	306	447
	2010	25	568	400	450	400	500
	2020	25	735	500	600	500	700
Zinc bromide	2000	20	560	600	600	500	600
	2005	20	632	650	650	550	675
	2010	20	704	700	700	600	750
	2020	20	840	800	800	700	900

TABLE 8 Initial Cost (in nominal $/kWh) for 10 Battery Technologies

Battery Technology	Year	Obs	Mean	Mode	Median	Quartile-1	Quartile-3
Lead acid	2000	54	185	200	190	150	200
	2005	54	182	190	185	150	200
	2010	54	179	180	180	150	200
	2020	53	184	200	180	150	200
Lithium iron disulfide	2000	21	853	1,000	850	800	1,000
	2005	21	758	900	775	663	900
	2010	22	664	800	700	525	800
	2020	31	622	800	600	500	800
Lithium polymer	2000	36	592	200	700	200	800
	2005	36	499	175	550	175	650
	2010	37	406	150	400	150	500
	2020	37	296	125	250	125	500
Nickel cadmium	2000	43	575	500	600	500	600
	2005	43	546	450	550	450	600
	2010	43	517	400	500	400	600
	2020	42	492	400	450	400	588
Nickel iron	2000	21	529	500	500	500	550
	2005	21	505	500	500	450	525
	2010	21	482	500	500	400	500
	2020	21	448	500	464	400	500
Nickel metal hydride	2000	43	569	600	583	350	600
	2005	43	498	400	492	275	550
	2010	43	426	200	400	200	500
	2020	42	382	180	300	185	475
Nickel zinc	2000	20	654	700	700	500	707
	2005	20	621	550	663	450	694
	2010	20	587	400	625	400	681
	2020	20	548	300	600	300	650
Sodium sulfur	2000	41	392	400	400	320	450
	2005	41	366	275	380	260	425
	2010	41	339	150	360	200	400
	2020	40	318	150	333	188	400
Zinc air	2000	25	483	500	500	300	545
	2005	25	435	450	450	300	498
	2010	25	387	400	400	300	450
	2020	25	339	300	350	300	400
Zinc bromide	2000	20	667	800	745	600	763
	2005	20	621	750	676	550	731
	2010	20	576	700	606	500	700
	2020	20	523	600	567	400	600

Fuel and maintenance costs in Table 3 are computed by multiplying the respondent-specified ratios by 5.8 cents. This base value of 5.8 cents/km represents the average fuel, lubrication, tire, and maintenance cost for a conventional car in 1993 [AAMA, 1996]. Battery replacement costs are excluded for the EV and the three HEVs. The conventional ICE is expected to have a fuel and maintenance cost advantage in 2000. The EV will have a slight advantage over the conventional vehicle by 2010 and a 14% (1.5 cents) advantage by 2020. HEV technologies are projected to have higher fuel and maintenance costs than the conventional vehicle through the year 2020. Only the ICE-powered HEV will come within 5% of the conventional vehicle cost by 2020.

BATTERY PERFORMANCE AND COST

BATTERY TECHNOLOGIES — Respondents were asked to provide achievable values for key characteristics of 10 promising battery technologies. They provided estimates for five characteristics: specific energy (Wh/kg), specific power (W/kg), shelf life (year), life in charge/discharge cycles, and initial cost ($/kWh). Tables 4-8 show a summary of the responses on battery characteristics. Many respondents chose not to respond to the battery technology questions, citing their lack of expertise in the area. Compared with the participation rate of nearly 95% for basic vehicle characteristics, the battery technology participation rate was low. Lead acid technology had the highest participation rate, nearly 60%. Four technologies, lithium polymer, nickel cadmium, nickel metal hydride, and sodium sulfur, had participation rates in the range of 42-48%.

Lithium polymer, zinc air, lithium iron disulfide, and sodium sulfur batteries have high specific energy, while the lead acid battery has the lowest. Lithium iron disulfide, nickel zinc, lead acid, and nickel cadmium batteries have high specific power, while zinc air and zinc bromide batteries have low specific power. Nickel iron, lithium polymer, nickel cadmium, and nickel metal hydride batteries have high shelf lives, while nickel zinc and lead acid batteries have low shelf lives. The sodium sulfur battery showed a small (0.1 year) decline in mean shelf life between 2010 and 2020. Nickel cadmium, nickel iron, and nickel metal hydride batteries are projected as being able to go through a high number of charge and discharge cycles. The lead acid battery has the lowest initial cost, while the lithium iron disulfide battery has the highest. The battery characteristics indicate that no one battery technology is superior in all respects.

INITIAL BATTERY PACK CHARACTERISTICS FOR THE EV — An EV may be characterized to match either a desired power level (acceleration capability) or a desired range. Because the currently available batteries are energy-limited, range may be a good criterion for characterizing an EV in the near term. However, the Delphi study used in our analysis is intended to project a long-term outlook, and therefore either mean power or mean range requirements may be used to characterize an EV. We first evaluated the initial battery pack characteristics on the basis of mean range requirements. Table 9 lists estimated power and battery pack mass necessary to meet the mean range requirements for the 10 battery technologies. Under this approach, a few battery technologies provide more power than required and have very high mass. Also, some battery technologies provide less than the mean power required and thus would not meet the performance (acceleration) requirements. Battery technologies that have low specific power and high specific energy show low power (inability to meet the acceleration requirements), while those with high specific power and low specific energy have very high mass (incompatibility with the overall vehicle characteristics). It was concluded that the initial battery pack characteristics for an EV should be evaluated on the basis of mean power requirements (listed in Table 1). The EV thus characterized will meet the acceleration requirements (will be road-worthy) and can be evaluated for other resultant characteristics, such as range, mass, and cost.

Table 10 lists the estimated initial battery pack characteristics for each battery technology for the four future years. Battery mass, energy, and initial cost are computed from the mean of responses to match the mean power requirements. EV range and battery life (in km) are computed by using information from related studies [Marr, 1994; Wang, 1994]. We used a set of baseline EV energy demand (from the battery pack) and corresponding battery mass estimates by Marr to compute range. We applied a 3.3% rate of change in energy consumption per 10% change in battery mass. This 3.3% rate of change in energy consumption is half the rate of change used for total vehicle mass [OTA, 1991]. Lifetime distance in kilometers represents the shorter of two distances: (a) shelf life times annual travel (17,600 km) and (b) number of cycles times half the range.

The initial battery pack characteristics estimated in this fashion for EVs do not match well with the basic vehicle characteristics specified by respondents in Table 1. Nearly all respondents, 92 of 93, answered the EV range question. They projected high range (179 km in 2000, increasing to 358 km in 2020) and nearly stable purchase price. Six of the 10 battery technologies can provide a 179-km range in 2000. The least expensive of these six batteries, nickel metal hydride, will cost $16,750. Subtracting this initial battery cost from the mean EV purchase price of $34,300 (see Table 2) leaves $17,550 for the remaining components, including an expensive controller [Cuenca and Gaines, 1996]. Respondents viewed three battery technologies as capable of providing a range of 358 km or more in 2020. The sodium sulfur battery is the least expensive of these

TABLE 9 Initial EV Battery Pack Power and Mass for the Mean Range [a]

Battery Technology	EV Power (kW)				Battery Pack Mass (kg)			
	2000	2005	2010	2020	2000	2005	2010	2020
Lead acid	153	223	306	485	989	1,303	1,610	2,265
Lithium iron disulfide	44	59	75	109	266	319	358	404
Lithium polymer	31	39	46	61	230	263	276	314
Nickel cadmium	103	142	185	290	545	730	930	1,391
Nickel iron	82	116	156	255	656	878	1,115	1,675
Nickel metal hydride	64	84	104	156	387	483	568	765
Nickel zinc	84	114	147	222	494	632	764	1,036
Sodium sulfur	40	53	67	98	277	357	438	613
Zinc air	21	27	34	51	225	274	312	417
Zinc bromide	42	60	81	126	450	590	732	1,014

[a] The mean range requirements are 179 km in 2000, 225 km in 2005, 270 km in 2010, and 358 km in 2020.

three at $21,120. The mean vehicle price in 2020 is $35,700, leaving $14,580 for the remaining components.

EVs are projected to become lighter over time. Their mean curb weight is 1,538 kg in 2000, dropping to 1,222 kg in 2020 (Table 1). On the other hand, the initial battery pack weight increases from 410 kg (nickel metal hydride) in 2000 to 620 kg (sodium sulfur) in 2020. Some inconsistency between basic vehicle characteristics and battery characteristics appears to exist in the responses. However, almost all respondents provided information on the desired EV characteristics, while only those familiar with the battery technologies responded to the battery questions. The mean basic vehicle characteristics appear to have been influenced by the respondents who were familiar with the vehicle characteristics, but not with the battery technologies.

EV BATTERY REPLACEMENT COSTS — On average, a conventional vehicle lasts 12-15 years and travels 170,000-210,000 km [Davis, 1995; Mintz, Tompkins, and Camp, 1994]. Because an EV does not idle while stopped and has fewer parts that are subjected to continuous wear and tear, we assumed an EV to be in use for 195,000-240,000 km, 15% longer. Since the initial battery pack has a shorter life than this, one or more replacement packs will be needed.

We computed battery replacement costs by using a sequential procedure. First, we computed intermediate values for battery specific energy, specific power, shelf life, cycles, and initial cost through linear interpolation. Next, we computed battery pack mass, energy, and cost for each of the 15 years an EV is in use for the mean power rating of the initial year (viz., 2000, 2005, 2010, or 2020). Next, we computed range and useable life in kilometers over a battery's shelf life and cycle life; then we computed battery replacement cost over both shelf and cycle lives and discounted it at 4% (real). Since battery technologies improve over time, the replacement batteries will have improved characteristics. For example, a year 2000 EV will require one or more replacement battery pack(s) over its life time (during the period 2003-2015). The projected improvements in battery characteristics will offer the buyer of a replacement battery pack two alternatives: (1) buy a battery pack that delivers enough power to match the motor's rating or (2) buy as big a battery pack as fits in the space available. The second alternative will cost more, but it will provide greater range because of improvements in the battery's specific energy. We assumed that the motor's power rating will be the constraining factor when purchasing a replacement battery (i.e., to keep costs down, an EV owner will not buy a battery pack with more power, even though doing so would increase the vehicle range). Finally, we summed the discounted replacement costs, distributed them over the respective lives (i.e., shelf life or cycles), and selected the higher of the two costs. The procedure excludes the cost of the initial battery pack because the Delphi questionnaire asked the respondents to include it in vehicle purchase price.

Figure 1 shows battery replacement cost and initial pack range for the 10 technologies. Four points are plotted for each technology, representing values for EVs produced in 2000, 2005, 2010, and 2020. In general, the replacement cost declined over time and the range increased. One exception is the sodium sulfur battery, for which the replacement cost is not projected to drop after 2010 (though range increases, a bigger battery pack is necessary to match the higher power rating in 2020). The changes in replacement cost are remarkable because they are visible even with the increases in mean power requirements. Only two batteries, lead acid and nickel cadmium, are projected to have their replacement costs under 6 cents/km in 2000 and 2005. The nickel iron battery will join them in 2010

TABLE 10 Characteristics of Initial EV Battery Pack [a,b]

Battery Technology	Year	Mass (kg)	Energy (Wh)	Initial Cost ($)	Range (km)	Life (km)
Lead acid	2000	430	17.040	3,150	110	32,100
	2005	440	18.530	3,370	110	38,400
	2010	450	20.030	3,590	120	45,200
	2020	460	22.340	4,120	140	59,400
Lithium iron disulfide	2000	400	38.700	33,010	250	61,500
	2005	410	43.160	32,310	270	71,600
	2010	410	47.610	31,610	300	81,800
	2020	370	50.630	31,480	330	101,300
Lithium polymer	2000	490	53.900	31,900	320	84,800
	2005	500	64.100	31,040	370	106,300
	2010	520	74.290	30,170	430	127,700
	2020	510	88.100	26,040	520	145,000
Nickel cadmium	2000	350	20.020	11,520	130	82,600
	2005	390	22,970	12,460	150	98,200
	2010	430	25,930	13,410	160	114,900
	2020	480	29,660	14,600	180	138,300
Nickel iron	2000	530	27,240	14,400	160	81,900
	2005	570	30,530	15,350	170	99,300
	2010	610	33,820	16,310	180	118,400
	2020	650	37,510	16,800	200	153,800
Nickel metal hydride	2000	410	29,440	16,750	190	82,000
	2005	440	34,180	16,670	210	94,000
	2010	470	38,930	16,590	230	106,100
	2020	490	43,570	16,670	260	117,700
Nickel zinc	2000	390	23,670	15,480	150	32,200
	2005	420	27,040	16,670	170	42,000
	2010	450	30,410	17,850	190	53,100
	2020	460	34,050	18,660	210	74,300
Sodium sulfur	2000	460	44,040	17,250	260	74,800
	2005	510	50,770	18,380	290	84,900
	2010	560	57,510	19,520	320	94,900
	2020	620	66,340	21,120	360	93,100
Zinc air	2000	730	85,110	41,120	420	66,500
	2005	760	97,140	41,670	470	76,800
	2010	800	109,170	42,220	520	87,200
	2020	810	118,960	40,350	570	94,300
Zinc bromide	2000	710	48,740	32,510	250	56,500
	2005	740	53,410	32,970	260	65,500
	2010	780	58,090	33,440	280	74,600
	2020	800	63,410	33,160	310	87,800

[a] For the mean power requirements of 66.7 kW in 2000, 76.4 kW in 2005, 86.1 kW in 2010, and 99.2 kW in 2020.

[b] Values are rounded to the nearest ten or hundred.

and nickel metal hydride in 2020. The respondents have high expectations for the lithium polymer battery. Its replacement cost dropped from 12 cents/km in 2000 to 6.8 cents/km in 2020, and it has nearly twice the range of the nickel metal hydride battery.

Results of the replacement cost analysis show the nickel metal hydride battery as capable of meeting the year 2000 mean-range requirement of 179 km at a cost of 7.5 cents/km. The nickel cadmium battery has a lower cost, 6 cents/km, but provides only a 130-km range. The lithium polymer battery improves its replacement cost by 26% between 2000 and 2005 and 19% between 2005 and 2010. The lithium polymer battery can also meet the mean-range requirements for 2005, 2010, and 2020 at the cost of 8.8, 7.1, and 6.8 cents/km, respectively.

As explained earlier, each battery pack in Table 10 and Figure 1 is characterized to meet the mean power requirements emerging from the Delphi data. The Delphi respondents specified higher vehicle power requirements in 2010 and 2020, thereby implicitly requiring bigger battery packs if the battery technologies that have low specific power are to be used. A nickel metal hydride battery pack with 66.7 kW of power in 2000 will weigh 410 kg, contributing an estimated 26% of the EV curb weight. A nickel cadmium battery pack with a shorter range (130 km) will weigh 350 kg and contribute 23% of the EV curb weight. Lithium polymer battery packs are estimated to be heavier, in the range of 500-520 kg; the increased mass results from the lower specific power rating of the technology. If the range expectations are lowered to 260 km or less, the nickel metal hydride battery can meet them at costs lower than those of the lithium polymer battery. Even the nickel metal hydride battery packs will weigh more (see Table 10) because of increases in the mean power requirements.

The mean power requirements of 66.7, 76.4, 86.1, and 99.2 kW and mean curb weights of 1,538, 1,444, 1,351, and 1,222 kg for the four future years were obtained from the basic vehicle characteristics responses. These numbers translate to 0.043, 0.053, 0.064, and 0.081 kW/kg, compared with the current desirable power-to-mass ratio of 0.074 kW/kg (0.045 hp/lb) for the conventional ICE. Cars had average power-to-mass ratios of 0.053 kW/kg (0.032 hp/lb) in 1981 and 1982 [Heavenrich and Hellman, 1996]. Individual models with even lower power-to-mass ratios were acceptable during the past energy price shocks. For example, the 1982 four-door Chevrolet Chevette equipped with a diesel engine had a power-to-mass ratio of 0.037 kW/kg [Automotive News, 1982]. Thus, although future EVs appear to be underpowered through 2010, their power-to-mass ratios are not unrealistic.

Among the battery technologies that have replacement cost under 10 cents/km, lead acid is the least expensive with very limited range, and lithium polymer is the most expensive, but with high range (see Figure 1). For a better balance between power and range, a combination battery pack of lead acid and lithium polymer batteries is the best combination. Advances in battery monitoring technology are predicted to make such mixing and matching of batteries feasible in portable computing [McCormick, 1996]. We analyzed hypothetical combination battery packs in which both lead acid and lithium polymer batteries would power an EV in the year 2020. The cost objective worked consistently, but power was low. We lowered the power requirement to 85 kW, assuming that the better speed-torque relationship of an electric motor would not require as high a power-to-mass ratio as an ICE. The results of the analysis are shown in Figure 2. Two curves, median and optimistic, are shown. The median curve shows results with the median values of Delphi responses, while the optimistic curve shows results with optimistic values for specific power, specific energy, and cost. The median responses show power increasing and range declining with increased share of the battery pack by lead acid batteries. The optimistic group for the lithium polymer battery expected higher specific power for it than did the optimists for the lead acid battery. This led to reductions in both power and range when the lead acid battery share increased. In both cases, the cost of the battery pack was reduced when lead acid battery share increased.

INITIAL BATTERY PACK CHARACTERISTICS FOR THE HEV — As discussed earlier, most respondents appear to assume that all hybrids are of the "range extender" type. A "range extender" HEV should provide the specified peak vehicle power while running on batteries. The battery packs will have 79.6 kW of power in 2000, 89.4 kW in 2005, 99.1 kW in 2010, and 108.6 kW in 2020. The resulting power-to-mass ratios (computed by using data from Table 1) are 0.051-0.086 kW/kg. Table 11 summarizes the estimated characteristics of the initial HEV battery packs for the 10 battery technologies. The estimates in the table are based on mean values of survey responses for such battery attributes as specific power, specific energy, and initial costs. For computing the range, we modified the baseline estimates by Marr [Marr, 1994]. We assumed that an HEV would consume the same amount of energy per kilometer as an EV and that its baseline battery pack mass would be similar to the baseline EV battery pack mass. Here, too, we used a 3.3% rate of change in energy consumption per 10% change in the battery pack mass. Lifetime distance in the table represents the distance computed either on the basis of shelf life or cycle life; the shorter of the two distances is shown. The first is computed as shelf life times the annual travel (17,600 km), while the second is the larger of (a) cycles divided by 365 times annual travel and (b) number of cycles times half the range.

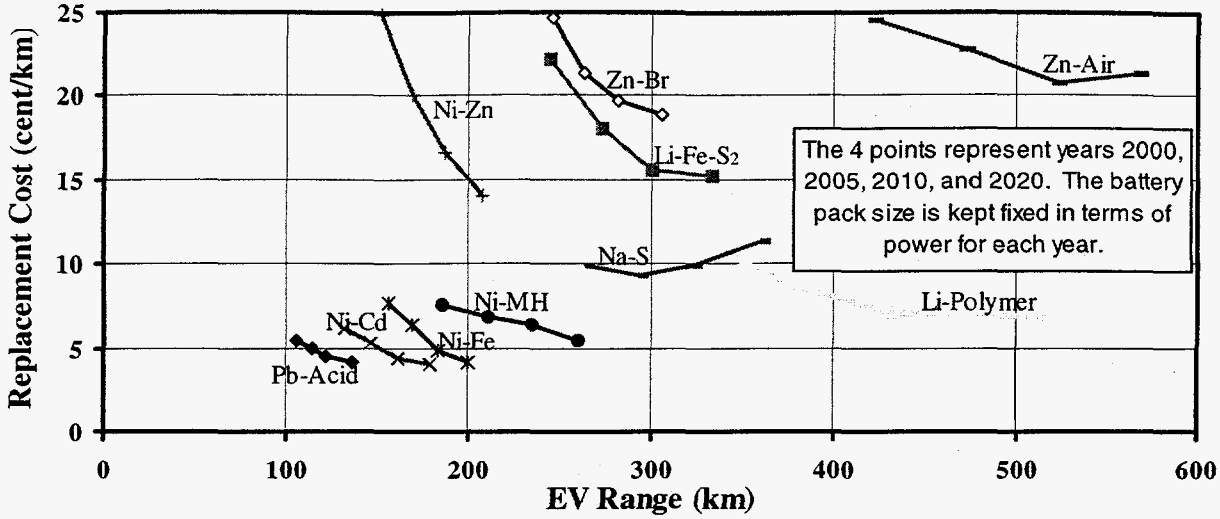

FIGURE 1. EV Battery Replacement Cost and Range Associated with the Mean Power Requirements

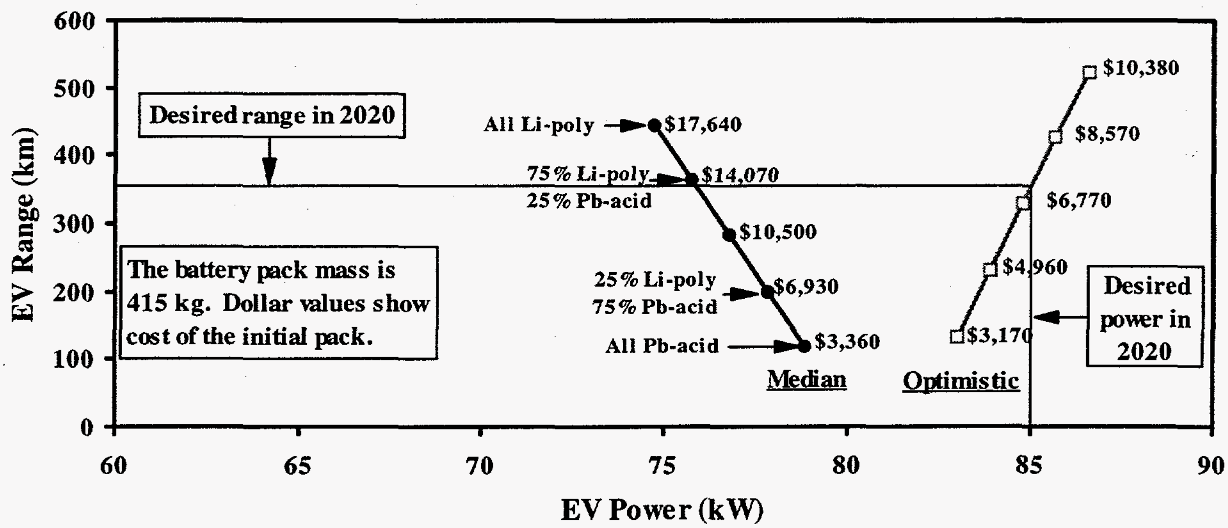

FIGURE 2. Analysis of Combined Lead-Acid and Lithium-Polymer Battery Packs for EV in 2020

TABLE 11 Characteristics of Initial HEV Battery Pack[a,b]

Battery Technology	Year	Mass (kg)	Energy (Wh)	Initial Cost ($)	Range (km)	Life (km)
Lead acid	2000	510	20,330	3,760	120	35,900
	2005	520	21,690	3,940	130	42,400
	2010	520	23,060	4,130	130	49,400
	2020	510	24,460	4,510	140	62,800
Lithium iron disulfide	2000	480	46,190	39,390	270	61,500
	2005	480	50,490	37,890	300	71,600
	2010	470	54,790	36,390	330	81,800
	2020	400	55,430	34,460	350	101,300
Lithium polymer	2000	580	64,320	38,070	350	84,800
	2005	590	74,920	36,400	410	106,300
	2010	590	85,510	34,730	470	127,700
	2020	560	96,450	28,510	550	145,000
Nickel cadmium	2000	420	23,890	13,750	150	93,200
	2005	460	26,870	14,590	160	108,800
	2010	500	29,840	15,430	180	116,900
	2020	520	32,470	15,980	190	138,800
Nickel iron	2000	640	32,510	17,190	170	90,800
	2005	670	35,720	17,980	180	108,600
	2010	710	38,930	18,770	200	127,900
	2020	710	41,070	18,390	210	161,600
Nickel metal hydride	2000	480	35,130	19,990	210	82,000
	2005	510	39,970	19,540	230	94,000
	2010	540	44,810	19,090	260	106,100
	2020	530	47,700	18,250	280	117,700
Nickel zinc	2000	470	28,250	18,480	170	36,200
	2005	490	31,620	19,510	190	46,500
	2010	520	35,000	20,540	200	58,000
	2020	510	37,280	20,430	220	78,600
Sodium sulfur	2000	550	52,560	20,580	300	74,800
	2005	600	59,370	21,530	320	84,900
	2010	650	66,190	22,470	350	94,900
	2020	680	72,620	23,120	380	93,100
Zinc air	2000	870	101,570	49,080	460	66,500
	2005	900	113,610	48,830	510	76,800
	2010	920	125,660	48,590	560	87,200
	2020	890	130,230	44,170	590	94,300
Zinc bromide	2000	840	58,160	38,790	270	56,500
	2005	870	62,510	38,640	290	65,500
	2010	900	66,870	38,490	300	74,600
	2020	870	69,420	36,300	320	87,800

[a] For the mean power requirements of 79.6 kW in 2000, 89.4 kW in 2005, 99.1 kW in 2010, and 108.6 kW in 2020.

[b] Values are rounded to the nearest ten or hundred.

Eighty-five out of 93 respondents (91%) answered the HEV range question under the basic vehicle characteristics. They specified total and engine ranges for an HEV. The resulting battery ranges are 145 km in 2000, 178 km in 2005, 212 km in 2010, and 244 km in 2020. Under our "range extender" design assumptions, nine battery technologies are capable of providing an all-electric range of 140 km or longer in 2000; of these, nickel cadmium is the least expensive at $13,750. The mean purchase price of an ICE-powered HEV is $37,080 in 2000 (Table 2), leaving $23,330 for the rest of the components. Six battery technologies, lithium iron disulfide, lithium polymer, nickel metal hydride, sodium sulfur, zinc air, and zinc bromide, can provide an all-electric range of over 200 km in 2010 and 2020. Nickel metal hydride is the least expensive of these at $19,090 and $18,250. An ICE-powered HEV is projected by respondents to cost $36,550 in 2010 and $38,050 in 2020, which would leave $17,460 in 2010 and $19,800 in 2020 for the rest of the HEV.

Respondents projected the mean HEV curb weight at 1,556 kg in 2000, 1,469 kg in 2005, 1,382 kg in 2010, and 1,265 kg in 2020. The estimated mass of a nickel cadmium battery pack is projected to be 420 kg in 2000, while the nickel metal hydride battery packs would weigh 540 kg in 2010 and 530 kg in 2020. A mid-size conventional car had a curb weight of 1,368 kg in 1993. The Energy Information Administration projects nearly stable transportation energy prices through 2015, increasing at a rate of 0.9% per year [EIA, 1996]. Such low growth in energy prices would not require dramatic increases in vehicle fuel economy. In a related ANL study, the conventional vehicle curb weight was estimated to drop 2% by 2000, 5% by 2010, and 7% by 2020 under a baseline scenario [Stodolsky, Vyas, and Cuenca, 1995]. Thus, the projected curb weight for the conventional mid-size car would be 1,340 kg in 2000, 1,300 kg in 2010, and 1,270 kg in 2020. The estimated weight of an HEV without its battery pack would be 1,136 kg in 2000, 842 kg in 2010, and 735 kg in 2020. These low curb weights will require increased use of lightweight materials, which will increase HEV costs.

HEV BATTERY REPLACEMENT COSTS — Earlier, we described a procedure for computing battery replacement costs for EVs. This procedure computes battery replacement intervals, assuming 17,600 kilometers per vehicle per year and a 15% longer vehicle life (in terms of life time usage) than the conventional ICE. The procedure computes replacement costs on the basis of both shelf and cycle lives and selects the higher of the two. We computed HEV battery replacement costs by means of this procedure.

The Delphi questionnaire sought experts' opinions on the future characteristics of batteries for use in both EVs and HEVs. Though it is possible to design batteries for specific end uses (such as higher specific energy for EVs and higher specific power for HEVs), all respondents provided one set of values for both EVs and HEVs. Therefore, we used the same battery characteristics for both vehicle types.

Figure 3 shows the computed battery replacement costs for the 10 technologies. The lead acid technology has the lowest replacement costs for 2000 and 2005. The nickel cadmium battery is ranked next, with estimated replacement costs at fractions of a cent higher. The nickel metal hydride technology provides a longer battery range, but it costs more (at least one and a half cents more per kilometer than nickel cadmium in 2020). Again, the lithium polymer technology is projected to improve dramatically between 2000 and 2020.

All battery technologies except lead acid can provide a range of 140 km or longer for 2000; the nickel cadmium battery has the lowest replacement cost, 6.3 cents/km, for this period. At 6.2 cents/km, the nickel iron battery would be the battery of choice for 2005 to meet the 175-km range requirement. The nickel metal hydride battery would be the battery of choice from 2010 onward, to meet the desired range of 210 km and higher; its estimated replacement cost is 7.3 cents/km in 2010 and 5.9 cents/km in 2020. If replacement cost were the controlling factor, the lead acid battery would be preferred through 2020, with a replacement cost ranging from 5.8 cents/km in 2000 to 4.1 cents/km in 2020. The lead acid battery is projected to have a range of 118-144 km through 2020. A majority of urban vehicles travel 45-48 km/day [Wang, 1994; NPTS, 1991]; the lead acid battery would be able to supply the necessary energy for that distance.

The U.S. government and the automotive industry have developed a partnership, the Partnership for a New Generation of Vehicles (PNGV), to develop high-fuel-economy vehicles. The need for such a vehicle arises from concerns about global warming and the fear of excessive reliance of the U.S. economy on imported oil. One of the technological options under consideration by PNGV is the development of a low all-electric range and low battery-power (or battery/ultracapacitor-power) hybrid electric vehicle. Such a vehicle may not be designed for, or expected to use, electricity from the electric grid. Any all-electric operation would be limited to low-speed (and low-acceleration) local driving and cruising. Separately, we analyzed battery replacement costs for a low-battery-power hybrid, assuming its batteries to have power equal to half the mean power specified by the Delphi respondents. We applied the same methodology, and the resulting battery replacement costs are shown in Figure 4. The pattern of battery replacement costs is similar to the "range extender" HEVs described above. Since the range on battery power is not a constraining factor for these HEVs, lead acid emerges as the least-cost battery technology, with nickel cadmium as the next near-term alternative.

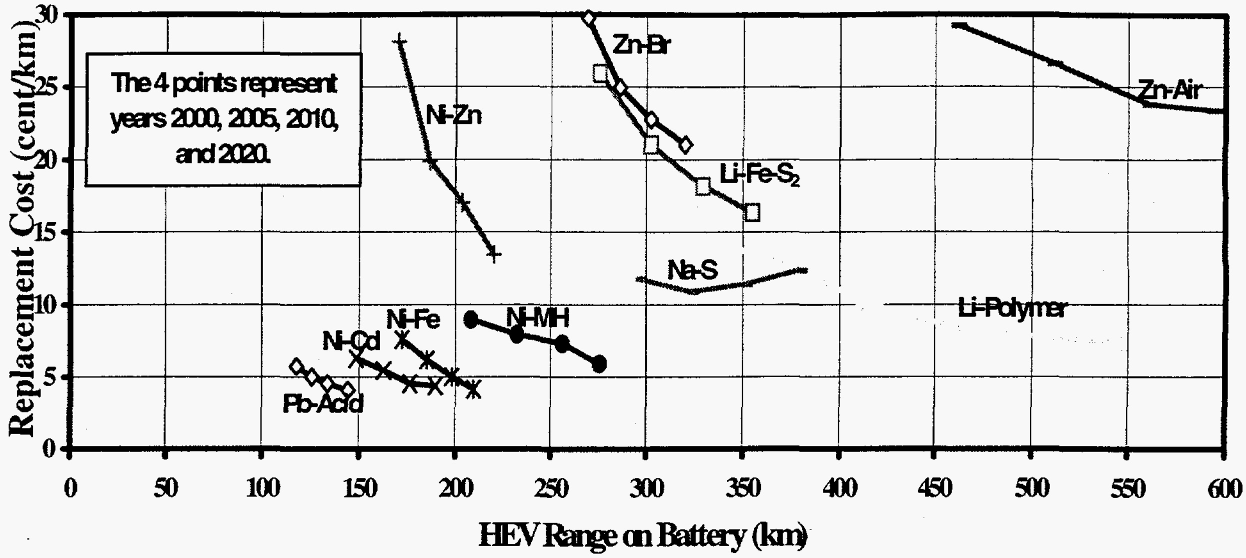

FIGURE 3. HEV Battery Replacement Cost and Range Associated with the Mean Power Requirements

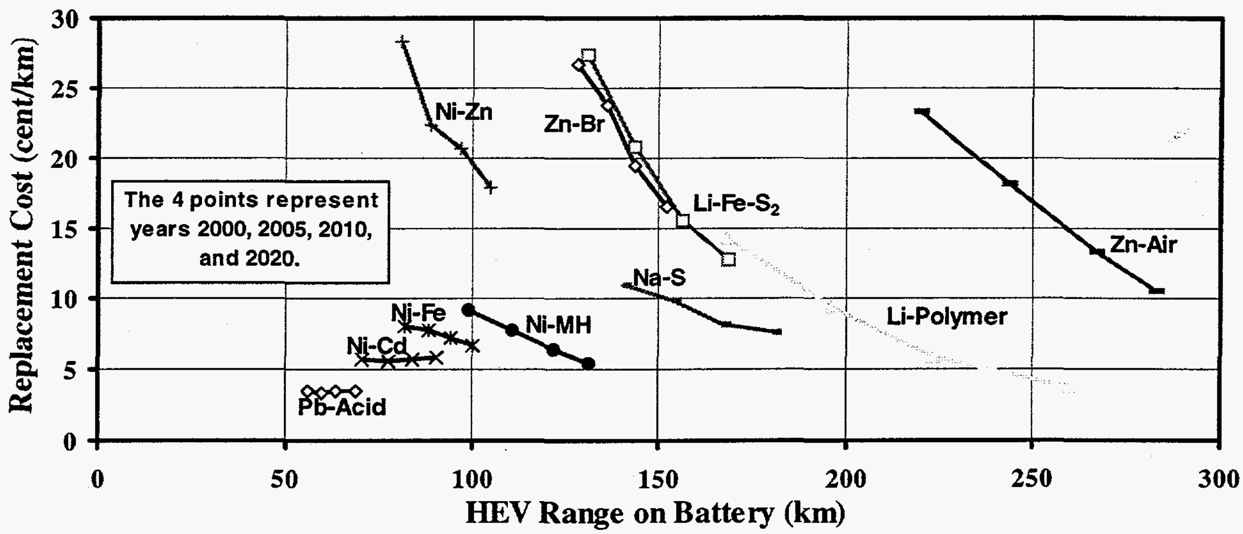

FIGURE 4. HEV Battery Replacement Cost and Range Associated with Half the Mean Power Requirements

The lithium polymer battery was estimated by this method to be a low-cost alternative in the long term.

It appears possible, in retrospect, that the survey questionnaire's structure guided respondents to think in terms of "range extender" HEVs rather than PNGV-type HEVs. The absence of separate battery questions for EVs and HEVs, and the nature of the cycle life question, would have promoted this type of response. The cycle life question asked for cycle life to 50% state of charge (SOC). A question valid for a PNGV-type HEV might have asked for cycle life if the battery were operated from 80% to 60% SOC. Since such a question was not asked, it is not possible to estimate the pattern of battery replacement costs for a PNGV-type HEV. Note that relatively few battery responses were obtained, so any increased complexity of the questionnaire might have been unproductive in any case.

VARIABLE OPERATING COSTS, INCLUDING BATTERY REPLACEMENT — Earlier, we analyzed fuel and maintenance cost responses under electric drive vehicle characteristics. The mean fuel maintenance costs for EVs and HEVs did not include battery replacement costs. Among the three HEV technologies, the fuel-cell-powered HEV is not expected to have a large battery pack. We added the above-discussed battery replacement costs to the EV and the other two HEV technologies and compared the results with that for conventional ICE vehicles.

First, we computed total variable operating cost for an EV or HEV when the battery technology of choice meets the mean range requirements. Figure 5 shows the results of this comparison. In 2000, the EV is powered by a nickel metal hydride battery pack and the two HEVs are powered by nickel cadmium battery packs. Lithium polymer is the battery of choice for EVs from 2005 onward, while nickel iron in 2005 and nickel metal hydride from 2010 onward are the batteries of choice for HEVs. The conventional ICE has the decided advantage of low variable operating cost. The EV has a slightly higher operating cost than the ICE-powered HEV through 2005 and lower operating costs thereafter. The gas-turbine-powered HEV has the highest operating cost through the analysis period. The respondents projected lower variable operating cost for the fuel-cell-powered HEV compared to the EV and other two HEVs.

We also computed total variable operating costs with reduced range expectations. We selected the nickel cadmium battery for the EV and the lead acid battery for HEVs, for all years. Although lead acid is the least expensive battery for the EV in 2000 and 2005, we did not select it because of its limited range. The results are shown graphically in Figure 6. Total variable costs dropped, making the EV more attractive than the two HEVs. However, the conventional vehicle still has an estimated cost advantage. Only if consumers viewed emission reduction and energy independence advantages as more important than these cost differences could the new technology vehicles gain significant market shares.

SUMMARY

We have presented some results of a two-stage Delphi study concerning EVs and HEVs. Expected vehicle characteristics and the future characteristics of 10 battery technologies were summarized. We evaluated initial battery pack costs and also analyzed replacement battery costs. The results are summarized as follows:

1. A large majority, 91-98%, of the 93 respondents to the second-stage Delphi questionnaire gave opinions on basic vehicle characteristics for EVs and HEVs. These characteristics include power, range, curb weight, and seating capacity.

- Respondents projected a 49% increase in mean EV power capability and a 36% increase in mean HEV power capability between 2000 and 2020.

- They projected a 100% increase in mean EV range between 2000 and 2020. For the HEV, they projected a 49% increase in total range and a 31% increase in the engine range between 2000 and 2020. The estimated battery-only range is 39% of the total in 2000 and 47% of the total in 2020. The high battery ranges imply to us that the candidate HEVs are seen by respondents as "range extenders."

- They projected a 21% reduction in the mean EV curb weight and a 19% reduction in the mean HEV curb weight between 2000 and 2020.

- They projected the EV to have fewer than five seats until 2020 and the HEV to have fewer than five seats until 2010.

2. A slightly lower number of respondents, 75-93%, gave opinions on vehicle purchase price and variable operating cost, excluding batteries.

- They projected a 102% increase in the conventional vehicle price by 2020 compared to that for 1993. They projected both the EV and the HEV to have higher initial prices than the conventional vehicle through 2020.

- They projected the conventional vehicle to have an advantage in terms of variable operating cost in 2000, even when the battery replacement cost was excluded. An EV would have a variable cost advantage beginning in 2010. All three HEV technologies would have higher variable costs compared with the conventional vehicle's through 2020.

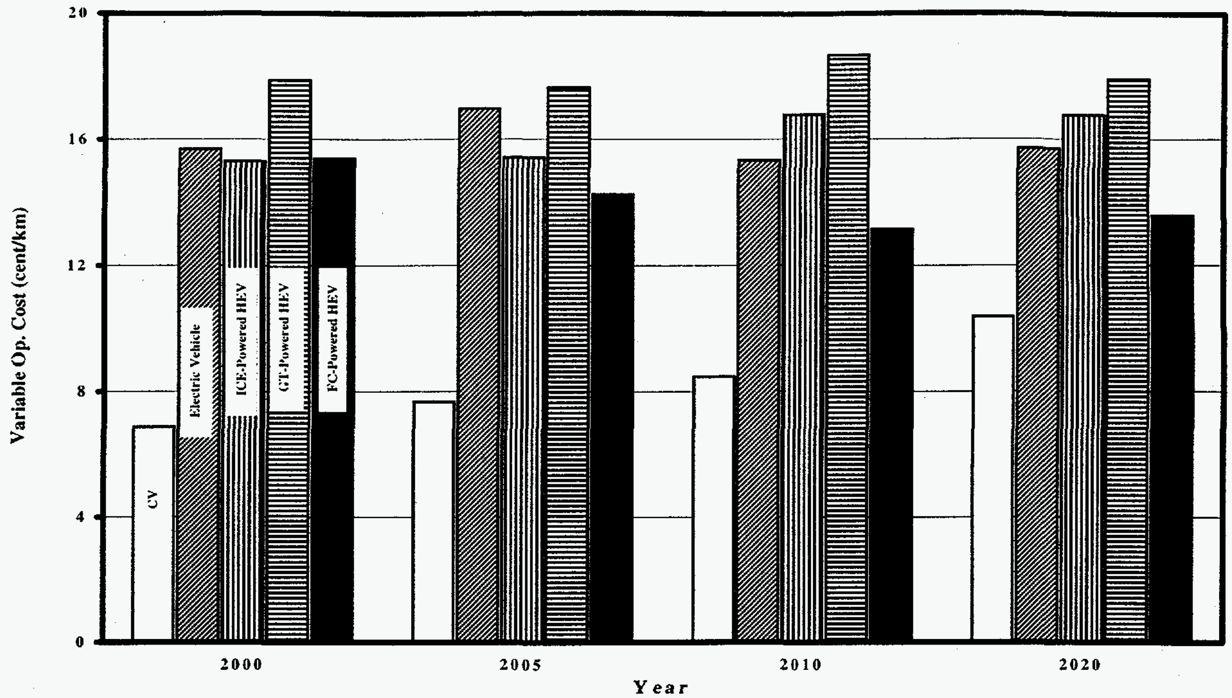

FIGURE 5. Variable Operating Costs, Including Battery Replacement Costs and Matching the Mean Range Requirements

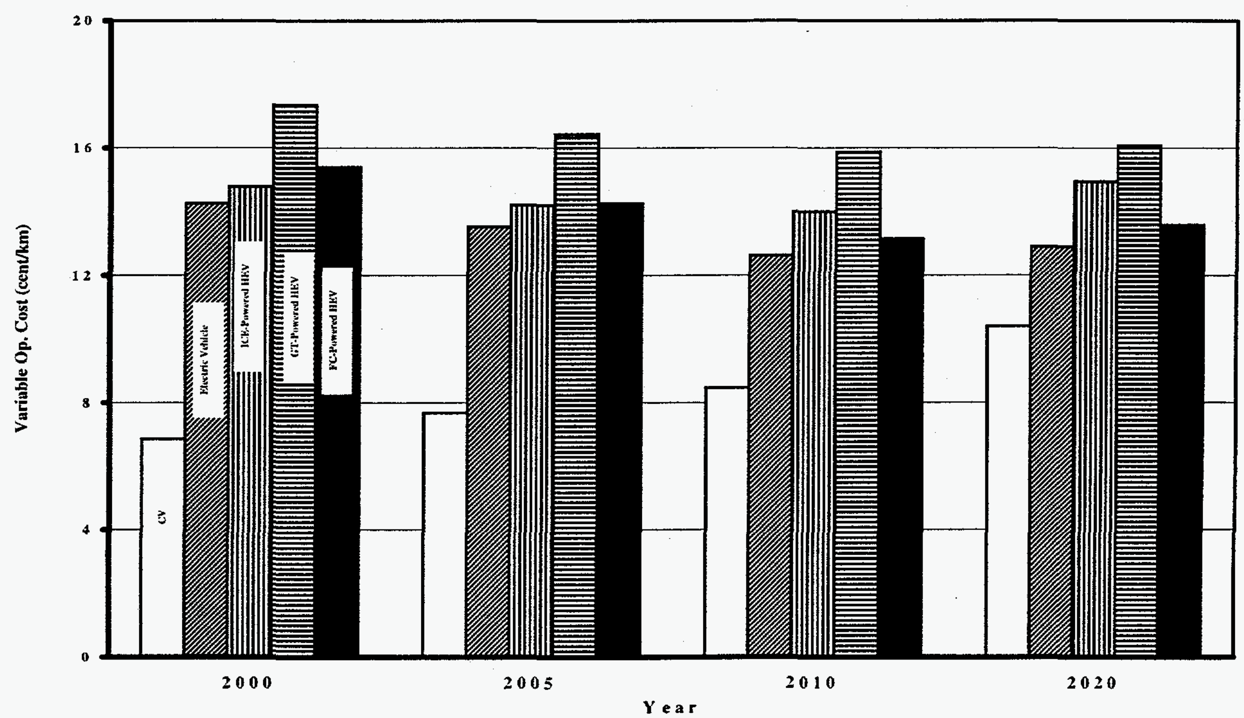

FIGURE 6 Variable Operating Costs with Less Expensive Battery, Ignoring the Mean Range Requirements

3. A smaller number of respondents, 22-59%, gave opinions on 10 battery technologies. They provided input on such future battery characteristics as specific energy, specific power, shelf life, number of charge/discharge cycles, and initial cost.

- They projected that almost all battery technologies would improve over time. The rate of improvement varies among technologies. No one battery technology is superior in all respects.

- The high mean-range requirements for EVs and HEVs will necessitate expensive battery packs, given the battery characteristics projected by respondents. The price of the initial battery pack will therefore make purchase price predictions very difficult to achieve. The mass of the initial battery is also expected to be high, making the mean curb weight predictions difficult to achieve.

4. We developed a procedure to compute battery replacement costs and computed these costs for both the EV and the HEV.

- Almost all battery technologies were projected to reduce their cost over time. The lithium polymer battery showed the highest rate of improvement.

- If the mean-range requirements are to be met, the battery replacement cost will be 6.8 cents/km or higher for EVs and 5.9 cents/km or higher for HEVs.

- If the EV range requirements are moderated as 130 km in 2000, 160 km in 2010, and 180 km in 2020, then relatively low battery replacement costs of 6 cents/km or lower are projected.

- HEV battery pack replacement costs can be reduced substantially with the use of lead acid batteries. The battery-only range will be limited to 115-145 km, but the battery replacement cost will be reduced to 4.1-5.8 cents/km.

- When battery replacement costs are added to variable operating costs, the respondents' battery characteristics predictions imply that the conventional vehicle would have a substantial operating cost advantage. Both EVs and HEVs reduce their total variable costs when the mean battery range requirement predictions are ignored and the least expensive battery is selected.

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REFERENCES

AAMA (1996), *Motor Vehicle Facts & Figures '95,* American Automobile Manufacturers Association, Detroit, Mich.

ANL (1996), *Electric/Hybrid Vehicle Study: Second Stage Results,* Center for Transportation Research, Argonne National Laboratory, Argonne, Ill.

Automotive News (1982), *1982 Market Data Book Issue,* Detroit, Mich.

Cuenca, R.M., and L.L. Gaines (1996), *Estimates of Electric Vehicle Production Cost,* Argonne National Laboratory, unpublished information.

Davis, S.C. (1995), *Transportation Energy Data Book: Edition 15,* Oak Ridge National Laboratory Report ORNL-6856, Oak Ridge, Tenn.

EIA (1996), *Annual Energy Outlook 1996,* Energy Information Administration, U.S. Department of Energy Report DOE/EIA-0383(96), Washington, D.C.

Heavenrich, R.M., and K.H. Hellman (1996), *Light-Duty Automotive Technology and Fuel Economy Trends through 1996,* U.S. Environmental Protection Agency Report EPA/AA/TDSG/96-01, Ann Arbor, Mich.

Marr, W.W. (1994), *Estimates of Energy Consumption of Electric and Conventional Vehicles,* Argonne National Laboratory, unpublished information.

McCormick, J. (1996), *The Battle between Lithium-Ion and Zinc-Air Batteries Has Begun,* Government Computer News / State & Local, Silver Springs, Md.

Mintz, M.M., M.M. Tompkins, and J. Camp (1994), *The IMPACTT Model: Structure and Technical Description,* Argonne National Laboratory Report ANL/ESD/TM-93, Argonne, Ill.

Ng, H.K., J.L. Anderson, and D.J. Santini, (1995) *The Prospects for Electric/Hybrid Vehicles, 2000-2020: First-Stage Results of a Two-Stage Delphi Study,* in Electric and Hybrid Vehicles — Implementation of Technology, SAE International Report SP-1105, pp. 123-135, Warrendale, Penn.

Ng, H.K., J.L. Anderson, D.J. Santini, and A.D. Vyas (1996), *The Prospects for Electric and Hybrid Electric Vehicles: Second-Stage Results of a Two-Stage Delphi Study,* in Technical Solutions to Alternative

Transportation Problems, SAE International Report SP-1189, pp. 111-130, Warrendale, Penn.

NPTS (1991), *1990 Nationwide Personal Transportation Survey: User's Guide for the Public Use Tapes,* Federal Highway Administration, U.S. Department of Transportation, Washington, D.C.

OTA (1991), *Improving Automobile Fuel Economy: New Standards, New Approaches,* Office of Technology Assessment, U.S. Congress Report OTA-E-504, Washington, D.C.

Stodolsky, F., A. Vyas, and R. Cuenca (1995), *Lightweight Materials in the Light-Duty Passenger Vehicle Market: Their Market Penetration Potential and Impacts,* Proceedings of the Second World Car Conference, University of California at Riverside, Riverside, Calif.

Wang, M.Q. (1994), *Vehicle Travel Patterns in the Four Studied Areas and Driving Cycle Selection for Simulating EV Energy Consumption and CV Energy Consumption and Emissions,* Argonne National Laboratory, unpublished information.