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Abstract

Regulators, policy analysts, automobile manufacturers, environmental groups, and others are debating the merits of policies regarding the development and use of battery-powered electric vehicles (BPEVs). At the crux of this debate is lifecycle cost: the annualized initial vehicle cost, plus annual operating and maintenance costs, plus battery replacement costs. To address this issue of cost, we have developed a detailed model of the performance, energy use, manufacturing cost, retail cost, and lifecycle cost of electric vehicles and comparable gasoline internal-combustion engine vehicles (ICEVs). This effort is an improvement over most previous studies of electric vehicle costs because instead of assuming important parameter values for such variables as vehicle efficiency and battery cost, we model these values in detail. We find that in order for electric vehicles to be cost-competitive with gasoline ICEVs, batteries must have a lower manufacturing cost, and a longer life, than the best lithium-ion and nickel–metal hydride batteries we modeled. We believe that it is most important to reduce the battery manufacturing cost to $100/kWh or less, attain a cycle life of 1200 or more and a calendar life of 12 years or more, and aim for a specific energy of around 100 Wh/kg. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Electric vehicle; Battery; Cost; Performance; Lifecycle

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1. Introduction

Regulators, policy analysts, automobile manufacturers, environmental groups, and others are debating the merits of policies regarding the development and use of battery-powered electric vehicles (BPEVs). Advocates of BPEVs point out that urban air pollution remains a serious problem in most cities of the US, and that in transportation, BPEVs are the cleanest solution (Hwang et al., 1994). Detractors argue that BPEVs are likely to be very costly, and that without

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subsidies harmful to producers and consumers alike, almost no one will buy and use BPEVs (Sierra Research, Inc., 1994).

There is no question that, per mile of travel, BPEVs offer significant environmental benefits. [1] First, they have no emissions where they are most damaging – near people – and in general their emissions are much lower than those from conventional vehicles. This is particularly true for areas that obtain the majority of their electricity from modern natural gas powerplants, and renewable sources (such as hydropower and geothermal power). Second, they will remain clean their entire lives, unlike very tightly controlled gasoline vehicles. Third, they are quieter than internal-combustion engine vehicles (ICEVs). Fourth, they do not use petroleum, except to the extent that a small number of powerplants still operate on fuel oil. Fifth, they do not require an unsightly and environmentally damaging urban fuel delivery infrastructure. Moreover, BPEVs do offer some benefits to consumers: the electric powertrain is very responsive, it turns on and off instantly, and it does not require much maintenance (Turrentine and Kurani, 1998). Of course, weighing against these consumer benefits are the drawbacks of a relatively short driving range and relatively long recharging time.

The crux of this debate is cost. If the BPEV lifecycle cost – the annualized initial vehicle cost, plus annual operating and maintenance costs, plus battery replacement costs – can be expected to be close to the ICEV lifecycle cost, then it is reasonable to make policies to encourage or even require the development and use of BPEVs. But if BPEVs are likely to be much more costly to manufacture and operate than are comparable ICEVs, then society must ask whether the social benefits of BPEVs justify any greater "private" costs to consumers or producers.

In order to shed some light on this question of the cost of BPEVs, we have developed a detailed model of the performance, energy use, manufacturing cost, retail cost, and lifecycle cost of BPEVs and comparable gasoline ICEVs. The model simultaneously designs a specific motor vehicle (a Ford Taurus or Ford Escort-class vehicle) to meet range and performance requirements specified by the modeler, and then calculates the initial retail cost and total lifecycle cost of the designed vehicle. Because the battery is by far the largest cost item in the BPEV analysis, its performance and cost of the battery are represented in particular detail.

This paper is organized as follows. First, other recent published analyses of the retail and lifecycle costs of BPEVs are briefly reviewed. Next, the design and operation of the cost model used in the analysis presented here is described. Then, the base–case cost parameters and base–case cost results are presented and discussed. Several sensitivity analyses are then performed, in which the impact on cost of varying critical parameters from their base–case values are explored. Finally, the paper concludes with a discussion of the implications of the principal findings.

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[1] However, Sierra Research, Inc. (1994) and Dixon and Garber (1996) have argued that indirect economic effects might negate the environmental benefits of BPEVs by using the following reasoning. If BPEVs are very costly, but subsidized internally by automakers, all automobiles will become more expensive as a result. Consumers may therefore be inclined to buy new (relatively clean) cars less frequently, and to retain their old (relatively dirty) cars longer. The disbenefit of having a dirtier ICEV fleet might then outweigh the benefit of having a few very clean BPEVs. With regard to this argument, we note that if the subsidy effect is assumed to apply to all of the ICEVs that a manufacturer produces, rather than just to vehicles produced for the market in "ZEV states," the effect is likely to be on the order of at most a few hundred dollars per ICEV. It is unclear if this small price increase would in fact produce a discernable effect on consumer purchasing behavior.

2. Overview of recent cost analyses

Tables 1 and 2 present the initial cost and lifecycle cost estimates from studies performed by government agencies, coalitions, and research organizations from 1994 to 1999. These tables are based on a recent review of the assumptions, methods, and results of these electric vehicle cost studies (Lipman, 1999a). All studies conclude that BPEV costs will be higher than conventional vehicle costs in the near-term, but a few studies suggest that BPEV costs could relatively quickly drop to levels comparable to those of conventional vehicles, particularly on a lifecycle basis (US Department of Energy, 1995; Moomaw et al., 1994). Most studies suggest that BPEV purchase costs are expected to remain a few to several thousand dollars higher than conventional vehicle costs, with lifecycle costs also remaining somewhat higher (US Government Accounting Office, 1994; Dixon and Garber, 1996; New York State Energy Research and Development Authority, 1995; Office of Technology Assessment, 1995; Vyas et al., 1998). Finally, one study concludes that BPEV purchase prices are likely to remain much higher than conventional vehicle prices, through 2010 (Sierra Research, Inc., 1994).

The differences in the results of the studies summarized in Tables 1 and 2 can be explained by differences in assumptions regarding the types of vehicles analyzed, the assumed volume of vehicle production, the range and energy efficiency of the analyzed vehicle, the life and cost of the battery,

Table 1
Summary of published estimates of BPEV purchase cost

Cost study	Total or incremental purchase cost price[a]			
Vyas et al. (1998):	2000	2005	2010	2020
Subcompact BPEV	(<10K/yr)	(10–40K/yr)	(>40K)	(>40K/yr)
	$18,500–41,400	$18,300–35,900	$17,800–32,900	$17,700–30,300
	$27,300–63,500	$27,100–53,900	$26,300–49,400	$26,000–44,100
NYSERDA, 1995	1998	2000	2002	2004
Compact BPEV	40,000/yr	41,000/yr	10,700/yr	243,000/yr
	$28,173	$25,606	$20,060	$18,290
Office of Technology Assessment	Subcompact	Mid-size	Subcompact	Mid-size
(1995): *Incremental Price*	2005	2005	2015	2015
(Retail Price Effect)	(24,000/yr)	(24,000/yr)	(24,000/yr)	(24,000/yr)
	$8090–56,600	$10,920–74,100	$2260–25,560	$3175–33,090
Sierra Research, Inc. (1994):	1998	2002	2006	2010
Small Passenger BPEV–*Incremental Price*	$10,000–27,143	$7000–17,254	$4250–20,280	$10,000–22,726
US Government Accounting	Handbuilt	1000/yr	10,000/yr	10,000/yr
Office (1994): Compact BPEV	$42,700	$28,700	$27,000	$18,300
Moomaw et al. (1994)	1995 (prototype)		1998 (20,000/yr)	
Purpose-Built BPEV	$60,515		$22,945	
US Government Accounting	1998		2005	
Office (1994): Minivan BPEV	$25,409–30,739		$20,318–22,254	
Dixon and Garber (1996)	1998–2002			
Compact BPEV	$3320–15,000 incremental cost/vehicle			

[a] Note that in some cases the figures refer to full retail prices of BPEVs, while in other cases the figures refer to incremental costs, relative to comparable conventional vehicles.

Table 2
Summary of published estimates of BPEV lifecycle cost

Cost study	Lifecycle cost			
Vyas et al. (1998)	2000	2005	2010	2020
Subcompact BPEV	(< 10K/yr)	(10–40K/yr)	(> 40K)	(> 40K/yr)
	$0.30–0.72/mi	$0.27–0.60/mi	$0.25 – 0.48/mi	$0.24–0.42/mi
	$0.44–1.08/mi	$0.39–0.89/mi	$0.37–0.72/mi	$0.33–0.60/mi
NYSERDA (1995)	1998	2000	2002	2004
Compact BPEV	40,000/yr	41,000/yr	107,00/yr	243,000/yr
	$0.36/mi	$0.33/mi	$0.27/mi	$0.24/mi
Moomaw et al. (1994)			1998 (20,000/yr)	
Purpose-built BPEV			$0.24/mi	
Dixon and Garber (1996) Passenger	1998–2002		post 2002	
BPEV Lifetime Incr. Cost Minivan	$1316–11,251		$1234– 6456	
BPEV-Lifetime Incr. Cost	$608–15,799		$1023–7920	
US Department of Energy (1995):	1998		2005	
Minivan BPEV	$0.24–0.39/mi		$0.22–0.37/mi	
US Government Accounting Office	Near term		Long term	
(1994): Compact BPEV	$0.53/mi		$0.31/mi	

and the costs of accessories and additional equipment needed for the BPEV. This additional equipment includes battery chargers, vehicle heating and cooling systems, and electrical power steering units.

In the studies performed to date there are major differences in these critical “aggregate” parameters (such as the energy efficiency of the vehicle, and the $/kWh cost of the battery), in part because all of the studies have simply *assumed* rather than modeled these parameter values. This appears to be a significant deficiency, and thus further insight can be gained from a detailed and integrated energy-use, manufacturing cost, and lifecycle cost model. The following section describes the development of such a model, with particular attention to variables that influence the life and cost of battery.

3. An integrated, detailed model of vehicle performance, initial cost, and lifecycle cost

The integrated model described below has three major parts:

- a sub-model of vehicle cost and weight;
- a sub-model of vehicle energy use; and
- an assessment of periodic ownership and operating costs.

The sub-model of vehicle cost and weight consists of a model of manufacturing cost and weight, and a model of all of the other costs – division costs, corporate costs, and dealer costs – that compose the total retail cost of a vehicle. The manufacturing cost is the materials and labor cost of making the vehicle, estimated for each of the nearly 40 sub-systems that make up a complete vehicle. This sub-model also performs detailed analyses of the manufacturing cost of batteries and electric drivetrains.

The sub-model of vehicle energy use is a second-by-second simulation of all of the forces acting on a vehicle over a specified drive cycle. The purpose of this sub-model is to accurately determine the amount of energy required to move a vehicle of particular characteristics over a specified drive cycle, with the ultimate objective of calculating the size of the battery system and drivetrain necessary to satisfy the user-specified range and performance requirements. (The cost of the battery system is directly related to its size; hence the importance of an accurate energy-use analysis within a lifecycle cost analysis.) The energy use simulation is a standard textbook application of the physics of work, with a variety of empirical approximations, to the movement of motor vehicles.

Periodic ownership and operating costs, such as insurance, maintenance and repair, and energy, are *in toto* about the same magnitude as the amortized initial cost, and hence are an important component of the total lifecycle cost of ownership and use. Because of this, and because these costs can vary with the vehicle technology, this final part of the model develops detailed estimates of the most important of these costs – maintenance and repair, and insurance.

The model has several hundred input variables, aside from “low-case” inputs separate from “high-case” inputs, and also aside from optional multiple inputs of the same variable. It occupies about 3 MB of storage space, and takes a couple of minutes to run on a personal computer. The model is detailed and integrated: all vehicle components are linked analytically to vehicle weight, power, cost, and energy use, and the resulting computational circularity is solved by iterative calculations. The separate and combined performance of the battery and drive system are calculated from second-by-second simulations that are the equivalent of simplified engine maps for ICEVs.

It is important to emphasize that this is a vehicle-design *and* vehicle lifecycle cost model; it designs vehicles that satisfy range and performance requirements over a particular drive cycle, as specified by the user, and then calculates the initial and lifecycle cost of that vehicle over the specified drive cycle. This ensures that the BPEV is optimized for the particular range and performance requirements specified by the user. The model is completely documented in Delucchi (2000a).

3.1. Key outputs of the model

The model reports vehicle characteristics, including performance, weight, lifetime, and fuel economy; manufacturing cost and weight, by major vehicle subsystem (body, powertrain, battery, and more); division costs, corporate costs, profits, dealers costs, and shipping; the lifecycle (levelized) cost per mile, broken down by cost component (vehicle, fuel, insurance, etc.); and a cost summary. Tables 6–18 in Appendix A show the full output of the model.

The lifecycle (levelized) cost is calculated in three steps. First, the present value (at specified interest rates) of every stream of periodic costs (fuel, insurance, maintenance and repair, and so on) is calculated. Then, this present value is annualized (or levelized) over the life of the cost stream. Finally, this annualized present value is divided by the calculated annual average mileage to produce a levelized cost per mile of vehicle use over its lifetime.

A useful way to express the difference between the lifecycle (levelized) cost per mile of the gasoline vehicle and the levelized cost per mile of an alternative is as the break-even gasoline price. The break-even gasoline price is that price of gasoline, including all excise taxes, at which the levelized cost per mile of the BPEV equals the levelized cost per mile of the baseline gasoline vehicle. This parameter is also provided in the model output.

As regards initial cost, it is important to emphasize that the *full production and retail cost* of the vehicle is calculated, and that this will not necessarily be the same as the *actual selling price* of the vehicle. The estimated manufacturer's "suggested" retail price is a function of the full production cost, which the model estimates, and marketing and demand considerations, which are not addressed.

4. Discussion of modeling inputs and methods

The following discussion provides some detail regarding the model inputs and calculation methods. These details include those concerning vehicle manufacturing and retail costs, battery lifecycle costs, vehicle energy use, other vehicle ownership and operating costs, and financial parameters related to vehicle purchase.

4.1. Vehicle manufacturing and retail cost

The model of vehicle cost and weight consists of an analysis of manufacturing cost and vehicle weight, and an accounting all of the other costs – division costs, corporate costs, and dealer costs – that compose the total retail cost. With these tools, the model calculates the weight and total retail cost (in 1997 $) of a conventional and an electric drive Ford Escort and Ford Taurus. Costs are estimated for low (less than 10,000 units per year), medium (10,000 to 100,000 units per year), and high (generally 100,000 units per year or more) production runs of electric drivetrains and batteries. [2] Maintenance and repair costs are also estimated as a function of the drivetrain production volume.

With regard to estimates of the manufacturing costs of key electric vehicle components, it is important to note that these costs have been estimated in detail using a range of data sources, and to some extent including forecasts of potential future improvements in these components. Particularly in the analysis of nickel–metal hydride (NiMH) battery costs, several different "generations" of NiMH battery technology have been analyzed, including future generations based on materials that are currently in the basic research/laboratory testing phase. However, in all cases, the analysis is constrained by the present-day state of knowledge of these components. In other words, improvements have not been assumed as a "matter of faith" that cannot be well-justified with the information currently available at the present time. However, in addition to economies of scale, electric vehicle component costs can also decline over time due to improvements in product design, improvements in basic material utilization rates, and the accumulation of "manufacturing experience". In the future, it is possible that the combination of these forces could lead to component costs that are even lower than those in our "high production volume"

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[2] In this paper, the "low", "medium," and "high" production levels vary from component to component, but this variation is arbitrary inasmuch as it is not the result of an analysis of the actual potential supplier markets for different components. Ideally, one would model demand and supply from the level of final vehicle sales back through the various supplier industries, and estimate the production volume scenarios accordingly. This, however, is beyond our scope. We assume that the resultant implicit inconsistencies between production volume scenarios is relatively unimportant.

and advanced technology generation cases, with lower overall vehicle and lifecycle costs resulting as well.

4.2. The vehicle manufacturing cost model

The manufacturing cost sub-model breaks a complete vehicle into nearly 40 parts, according to the "uniform parts grouping" system used by the automobile industry. The major groups (or divisions) in this system are the body, the engine, the transmission, and the chassis. For each of the part groups, the model-user enters the weight of the material, the cost per pound of the material, the amount of assembly labor time required, the wage rate for labor, and the overhead on labor.

For purposes of calculations within the model, material costs plus the burdened labor cost equals the total variable manufacturing cost. To this variable manufacturing cost are added fixed costs at the division and the corporate level: buildings, major executives, engineers, accountants, corporate advertising, design and testing, legal, and so on. Finally, corporate profit, dealer costs, and shipping costs are added to produce the manufacturer's suggested retail price (MSRP).

The data for the baseline gasoline ICEVs (a Ford Taurus and a Ford Escort) are from cost analyses done by experienced automotive consultants (American Council for an Energy Efficient Economy, 1990; Energy and Environmental Analysis Inc., 1998). The baseline weight and cost data for the approximately 40 subparts sum up to the actual weight and MSRP of the gasoline Taurus and Escort. To estimate the manufacturing cost and weight of BPEVs, the entire parts grouping system is used to remove those parts groups that are not used in BPEVs, and to add parts groups, such as the electric drivetrain and the traction battery, that are in BPEVs but not ICEVs. Cost functions for the motor and controller are then developed, on the basis of a detailed review and analysis of available information (Lipman, 1999b). For the BPEVs, a complete heating and cooling system is included, along with an on-board charger (with off-board charging equipment accounted separately), regenerative braking, and battery thermal management.

The division cost is equal to a fixed cost plus an additional cost assumed to be proportional to the manufacturing cost. The corporate cost is equal to a fixed cost, plus an additional cost assumed to be proportional to the manufacturing-plus-division cost, plus the opportunity cost of money invested in manufacturing. The corporate profit is taken as a percentage of the factory invoice. The dealer cost is equal to a fixed cost, plus an additional cost assumed to be proportional to the factory invoice to the dealer, plus the cost of money to the dealer. The shipping cost is assumed to be proportional to vehicle weight, and the average shipping distance is assumed to be the same for ICEVs and BPEVs.

Finally, the model includes a detailed accounting of vehicle life and salvage value. Some of the features of this accounting are discussed below, and complete details are presented in Delucchi (2000a).

4.3. The lifecycle cost of the battery

Four types of batteries are examined: advanced, sealed lead/acid (Pb/acid); NiMH (a current-technology case, "Gen2," and an advanced-technology case, "Gen4"); lithium-ion (Li-ion); and a high temperature lithium–aluminum/iron–sulfide battery (Li–Al/Fe–S). For each battery, weight, cost, and performance parameters are developed. These battery types/parameters are user-selectable within the model.

In most if not all other BPEV cost analyses, the battery cost is estimated simply as the product of an assumed cost per kWh and the total number of kWh. However, this method assumes that the cost per kWh does not vary with the design of the battery, and since the cost *does* vary with design, it is better is to estimate cost as a function of battery-design parameters. Moreover, in other published cost analyses, the lifetime of the battery, which is a critical parameter in the estimation of the lifecycle cost, is simply a fixed number of cycles to 80% depth of discharge. However, the actual number of cycles that a battery will last is related nonlinearly to the average depth of discharge, and depends also on the point at which the battery is assumed to have "died".

In this analysis, battery lifecycle cost is estimated as a function of the following major parameters, most of which are calculated from other parameters (there are many other minor cost parameters):

- The \$/kg manufacturing cost, estimated as a function of the Wh/kg specific energy of the battery. The \$/kg versus Wh/kg functions are derived from the detailed battery analyses by Lipman (1999c) and Gaines and Cuenca (2000). [3] The Wh/kg specific energy of the battery is estimated as a function of the W/kg specific power, and the specific power, in turn, is estimated on the basis of the maximum power required over the drive cycle. These functions (\$/kg versus Wh/kg, and Wh/kg versus W/kg) represent real tradeoffs in battery design and manufacturing, and allow for the optimization of the battery for the specified range and performance requirements.
- The weight of the battery, estimated as a function of the specific energy, the driving range, and the vehicle efficiency.
- A recycling cost coefficient (\$/kWh) that can be positive or negative depending on whether or not the value of recovered material outweighs the cost of recycling.
- The life of the battery, estimated as the shorter of the calendar life and the cycle life. The cycle life is estimated as a function of the depth of discharge, and the capacity of the battery when it is discarded. The average daily depth of discharge is estimated as a function of the driving range of the BPEV.
- A battery resale value if the vehicle is scrapped with remaining battery life. The resale value is assumed to be proportional to the remaining battery life: 70% of the initial cost of the battery multiplied by the percentage of remaining battery life.
- The efficiency of the battery, estimated second-by-second over the specified drive cycle as a function of the battery resistance, voltage, and power.
- The weight and size of the battery tray, tie downs, electrical auxiliaries (such as bus bars), thermal management systems, and on-board charger. These are estimated as a function of battery parameters, temperature, and other factors.

It is important to emphasize that in the model the battery is *designed* to be as light as possible for the user-specified range and performance mission. First, the battery is required to have the amount of power necessary to exactly meet the performance requirement (for example, to be able to accelerate from zero to 60 mph in the same time that it takes the comparable gasoline ICEV) –

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[3] Kalhammer et al. (1995), Kalhammer (1999) and Vyas et al. (1997) also present data on battery characteristics.

and no more. Given the required power, the specific power is calculated. With the calculated specific power the corresponding specific energy is calculated, from the functions that characterize the tradeoff between power density and energy in battery design. The lower the required specific power, the higher the specific energy; hence, by having only as much power as is required by the performance standard, the specific energy of the battery and therefore the efficiency of the vehicle is maximized.

4.4. Vehicle energy use

Energy use is a central variable in economic, environmental, and engineering analyses of motor vehicles. The energy use of a vehicle directly determines energy cost, driving range, and emissions of greenhouse gases, and indirectly affects initial cost and performance. It therefore is important to estimate energy use as accurately as possible.

In this analysis, the energy-use sub-model calculates the energy consumption of BPEVs and ICEVs over a particular trip, or drive cycle. The energy consumption of a vehicle is a function of trip parameters, such as vehicle speed, road grade, and trip duration, and of vehicle parameters, such as vehicle weight and engine efficiency. Given trip parameters and vehicle parameters, energy use is calculated from first principles (the physics of work) and empirical approximations (e.g., as in Gillesspie, 1992). The base–case drive cycle is the Federal Urban Drive Schedule (FUDS) that is used in conjunction with other driving cycles by the US Environmental Protection Agency to test the fuel economy and emissions of motor vehicles.

Thus, given a drive cycle and desired vehicle range, the model calculates the total amount of propulsion energy required. This is then used to design the battery to provide exactly the performance required (discussed below), and no more.

Vehicle efficiency. The vehicle efficiency is calculated from the efficiency or energy consumption of individual components (the battery, the engine, the transmission, the motor controller, and vehicle auxiliaries), the characteristics of the drive cycle, the characteristics of the vehicle, the requirements of battery thermal management, and the requirements of cabin heating or cooling (in the base case, we assume year-round “average” heating and cooling needs). The model calculates the extra energy made available by regenerative braking, for the particular drive cycle specified by the user. The efficiency of the battery, electric motor, motor controller, and transmission are not input as single values over the entire drive cycle (as in most other cost analyses), but rather are calculated second by second from look-up tables (“maps”) of efficiency as a function of torque and rpm or other parameters.

Vehicle efficiency is circularly related, via vehicle weight, to many vehicle components and cost parameters. For example, if the driving range is increased, the amount of battery needed increases, which in turn increases the amount of structural support. The extra battery and structure make the vehicle heavier and less efficient, so that even more battery is needed to attain a given range, and so on. These circularities are resolved, and a mutually consistent set of values are converged upon, through iterative calculations.

Vehicle performance. The model designs the BPEVs to satisfy performance requirements specified by the user. The user specifies the desired amount of time for the BPEV to accelerate from any starting speed to any ending speed, over any grade, and the required motor power is then calculated (using calculated or input data on vehicle weight, component efficiency, drag, air density, rolling resistance, and so on). In the base case, the BPEV is assumed to have the same acceleration time from 0 to 60 mph as has the baseline gasoline ICEV. [4] The formulae used in the performance design calculation are the same as those used in the drive-cycle energy-use calculations.

In these calculations, the maximum power of the BPEV is circularly related to every component that (in vehicle design) actually is related to vehicle performance (see foregoing discussion of circularity in energy efficiency calculations). This ensures that all of the components related to vehicle performance are capable of meeting the maximum power needs of the modeled vehicle.

4.5. Ownership and operating costs other than energy

Insurance. The lifecycle cost aspect of the model handles insurance payments in some detail. This begins with an estimate of the monthly premium for comprehensive physical-damage insurance and liability insurance for a reference vehicle. Then, a relationship is formulated between the liability and physical-damage insurance premiums, and the value and annual travel of a vehicle. Generally, premiums are nearly proportional to vehicle miles traveled (VMT) and vehicle value. [5] With this relationship, along with estimates of the value of the modeled vehicle relative to the value of the reference vehicle and of the VMT of the modeled vehicle relative to the VMT of the reference vehicle, the insurance premiums for the modeled vehicle are estimated relative to the estimated premiums for the reference vehicle. The user can also specify the number of years that physical-damage insurance is carried (typically about five), in order to represent accurately the actual stream of insurance payments over the life of the vehicle.

Home recharging. The cost of home recharging is estimated as a function of the initial cost of a home recharging system (high-power circuit, and charger box), the interest rate, and the amortization period of the investment. The model calculates the length of time required to fully recharge the battery given a voltage and current input by the user, and the size of the battery required to satisfy the input vehicle range and power.

The retail cost of fuel or electricity. The cost of gasoline is calculated on the basis of user-specified feedstock costs, fuel-production costs, distribution costs, and retail costs. The cost of electricity is entered directly as an input variable. (In the base case, we assume that off-peak power costs $0.06/kWh.) Federal and state fuel excise taxes are handled separately (see below).

Maintenance and repair. The cost of maintaining and repairing a motor vehicle is one of the largest costs of operating a motor vehicle, on a par with the cost of fuel and the cost of insurance. Because the maintenance and repair (M&R) cost is relatively large, and is different for BPEVs than for ICEVs, special attention is given to it.

First, a relevant set of M&R costs are defined. Then, a year-by-year M&R schedule is estimated for the baseline gasoline ICEV. Estimated M&R costs for the BPEV, relative to the estimated M&R costs for the gasoline ICEV, are then established. This is done by identifying the kinds of

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[4] The peak horsepower of the baseline gasoline ICEV is an input variable. Given this input power, and other vehicle and drive-cycle characteristics, the model can calculate the acceleration time for the baseline gasoline vehicle.

[5] BPEVs may be less likely to be stolen than ICEVs because of their relatively low driving range (and the prospect of a thief being stranded as a result), but we do not quantify this potential effect on insurance rates.

M&R costs that are different for BPEVs than for ICEVs, along with the costs that are the same for ICEVs and BPEVs.

This M&R cost analysis is based mainly on the comprehensive data on sales of motor-vehicle services and parts reported by the Bureau of the Census (1995). These Census Bureau data are used to estimate M&R costs per LDV per year, and then to compare the results with estimates based on other independent data. Estimates by Federal Highway Administration (1992) are then used to transform the Census' estimates into a year-by-year M&R cost schedule. Finally, the adjusted year-by-year maintenance and repair cost data series are converted to a net present value, which then is levelized to produce a financially equivalent uniform annual cost series over the life of the vehicle.

Replacement tires. The cost per mile of tires is calculated as a function of the initial cost of the tires, the life of the tires and the interest rate. The model user specifies the life of the tires on the baseline gasoline vehicle, and then the life of the BPEV tires is calculated on the basis of the weight of the BPEV relative to the weight of the gasoline vehicle. Thus, if a BPEV weighs more than the baseline ICEV, then its tires will be replaced sooner and hence will have a higher lifecycle cost. To better reflect real consumer behavior, the tires are assumed to be not replaced if the last replacement interval is near the end of life of the vehicle.

Vehicle registration. The baseline assumption replicates the practice in most states and calculates the registration fee as a function of vehicle weight (i.e., heavier vehicles pay a higher fee).

Safety- and emissions-inspection fee. In the base case, gasoline ICEVs are subject to a safety- and emissions-inspection fee, but BPEVs are subject to a safety-inspection only, not an emissions inspection. BPEVs are therefore assumed to have a somewhat lesser associated inspection fee.

Parking, tolls, fines, and accessories. In the base case, these costs are the same for all vehicles.

Federal, state, and local excise taxes. The cost per mile of the current government excise taxes on gasoline is estimated, and then the cost per mile for the other vehicles relative to this is calculated by using a scaling factor (0.0 to 1.0) specified by the user. In the base case, BPEVs and ICEVs pay the same tax per mile, so that government revenues from highway users (for the highways) would be the same regardless of the type of vehicle or fuel (i.e., the scaling factor just mentioned is assumed to be 1.0).

The dollar value of air external costs. The model calculates the external cost per mile of emissions of urban air pollutants, emissions of greenhouse gases, noise, and petroleum use. (The external cost is the imputed dollar value of un-priced environmental and energy impacts of motor-vehicle use.) The pollution and greenhouse-gas cost is estimated on the basis of user-specified emission rates of tailpipe volatile organic compounds (VOCs), evaporative VOCs, carbon monoxide (CO), oxides of nitrogen (NO_x), oxides of sulfur (SO_x), particulate matter (PM), benzene, formaldehyde, 1,3-butadiene, and acetaldehyde, and fuel-cycle greenhouse-gas emissions (in g/mile), as well as user-specified damage values (in $/kg; Delucchi, 2000b). The $/kg figures are estimates of the dollar value of the impacts of pollution on human health, visibility, agriculture, and forests. Note, though, that these external cost estimates are included only in one sensitivity analysis; they are not in any of the other results. Not included at all are any other non-monetary environmental or consumer benefits or disbenefits (such as the disadvantage of low range, the convenience of home recharging, any loss of cargo space due to the battery pack, or the potential inconvenience of low public charging station availability).

Year-by-year mileage schedule. The model requires as inputs a year-by-year mileage accumulation schedule for the baseline gasoline vehicle, and a separate schedule for the BPEVs. This schedule is created from a continuous function that relates age to mileage; the user specifies the value of the coefficients in this function in order to produce the desired mileage schedule.

4.6. Financial parameters for vehicle purchase

A typical "weighted-average" vehicle purchase is estimated within the model by calculating or taking as input a detailed set of financial parameters. These parameters include: the fraction of new car buyers who take out a loan to buy a new vehicle; the amount of the average down-payment on the car (input as a fraction of full vehicle selling price); the length of financing period for cars bought on loan (in months); the real annual interest rate on loans taken out to buy a new car, before taxes; the real annual interest rate foregone on cash used for transportation expenditures, before taxes (the opportunity cost of cash used for down-payment or outright purchase); the effective (average) income tax paid on banking interest earned, after deductions; and whether or not interest payments are deducted from taxable income. The model treats loan payments as an ordinary cost, to be discounted by the personal opportunity cost of money. [6]

If desired, a discount rate can be specified to apply to the annual mileage. This allows the user to perform a quasi cost-benefit analysis, in which miles of travel are the "benefit" of travel, and are discounted (or annualized) in the same way as that of the costs. It turns out that if one assumes different mileage schedules for different vehicles, then whether or not one treats VMT as a benefit and applies a discount rate can make a large difference in the overall cost per mile results. However, in all cases presented here, the BPEVs and ICEVs are assumed to be driven the same number of miles per year, and the miles of travel are not discounted.

The financial cost sub-model also performs a highly simplified macro-economic simulation. In essence, it assumes that the interest rate, the fraction of new car buyers who take out a loan, and the length of the financing period are a nonlinear function of the value of the vehicle.

5. Presentation and discussion of the results of the analysis

5.1. Organization

Table 3 summarizes estimates of the retail cost and the break-even gasoline price, for the base case (high-volume production, FUDS, etc.), and for several scenarios (low-volume production, highway cycle, etc.). It shows results for two different driving ranges for each battery technology.

Detailed tables of results are given in Appendix A (Tables 6–18). The detailed tables present results for the Ford Taurus (results for the Escort are in Delucchi, 2000a) and four kinds of

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[6] The opportunity cost is the net benefit foregone from using a resource instead of using it in its next most beneficial use.

batteries (Pb/acid, NiMH Gen2, Li-ion, and NiMH Gen4), in high-volume production. The Appendix A tables of results are grouped by battery type. In all these detailed tables, the drive cycle is the aggregated FUDS cycle. Also, in all these Appendix A tables, we have set the 0–60 acceleration performance of the BPEV to be the same as that of the gasoline vehicle, which is 9.3 seconds. [7] For each vehicle, we show results for six different driving ranges.

In this paper, only the detailed manufacturing cost and weight results for the NiMH Gen2 battery are presented. Delucchi (2000a) shows the manufacturing cost and weight for vehicles with the other batteries.

5.2. Initial cost: base–case results

In all cases analyzed, and indeed in most conceivable cases, the retail cost of the BPEV is higher – usually much higher – than the $20,085 retail cost of the baseline ICEV Taurus or the $14,909 retail cost of the baseline ICEV Escort (Table 3). The higher initial cost of the BPEV is due mainly to the high cost of the battery. Batteries usually cost at least $300/kWh, at the retail level, and typically must supply 30 or so kWh – resulting in a retail level total cost of on the order of $9000 in many cases (see "cost summary" and "vehicle characteristics" tables in Appendix A). Thus, the BPEV with a Pb/acid battery and a short range is the least expensive, because this battery has a low cost per kWh, and relatively few kWh are needed to supply the relatively short range. However, the battery in this vehicle must be replaced a few times, and this increases the lifecycle cost.

Also, the retail cost differential for the BPEVs compared with the ICEVs is greater for the BPEV Escort than for the BPEV Taurus. This is on account of the relatively low cost of the ICE drivetrain in the ICEV Escort. [8] See Table 3 and Delucchi (2000a) for details.

5.3. Lifecycle cost (break-even gasoline price): base–case results

In Tables 3 and 4, the lifecycle break-even gasoline price is presented, rather than the lifecycle cost per mile, because most people are familiar with gasoline prices, but do not understand immediately whether a cost difference of, say, a penny per mile is relatively large or small. The lifecycle break-even gasoline prices (1997 $/gal) can be compared with the Energy Information Administration (2000) most recent projection that the price of gasoline, including Federal and State but not local taxes, will hold steady at $1.29/gal between 2005 and 2020 (in 1997 $). [9] Local taxes would add about $0.01/gal.

In the base case, there are only two combinations of vehicle type, battery type, production scenario, and driving range that result in break-even gasoline prices of under $2.00 per gallon: the NiMH Gen4 battery, in a high production volume Ford Taurus, with 70 mile and 100 mile driving

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[7] Due to the relatively high torque at low RPMs of electric motors compared with gasoline engines, EVs with the same acceleration time from 0 to 60 mph as ICEVs will tend to have faster acceleration times from 0 to 30 mph.

[8] The manufacturing cost of the engine and transmission per unit horsepower is almost 40% less for the Escort than the Taurus.

[9] The EIA's projections were made before the recent run-up in gasoline prices.

Table 3
Summary of results from performance and cost model[a]

Type of battery	Pb/acid		NiMH Gen2		Li-ion		NiMH Gen4	
Driving range (miles)	65	110	90	165	140	260	100	190
Retail cost, Taurus ($)								
Base case	24,553	29,422	28,034	35,759	27,678	32,448	25,487	29,692
Highway cycle	24,623	28,276	27,706	34,422	27,485	31,879	25,346	29,215
Low-volume production	36,566	44,955	44,920	61,801	52,942	72,819	40,357	50,563
10% less power	23,789	28,039	27,116	34,208	26,648	30,894	24,716	28,542
Retail cost, Escort ($)								
Base case	19,784	23,384	22,725	28,822	22,280	25,948	20,623	23,904
Highway cycle	19,566	22,574	22,518	27,893	22,179	25,563	20,540	23,571
Low-volume production	30,726	36,782	37,826	50,921	44,369	60,053	34,117	42,157
10% less power	19,218	22,434	22,038	27,659	21,517	24,785	20,055	23,075
Break-even, Taurus (*$/gal*)								
Base case	2.64	4.14	4.19	6.66	2.77	4.33	1.83	2.91
Highway cycle	3.71	5.63	6.26	9.60	4.11	6.40	2.59	4.20
Low-volume production	6.01	8.69	9.96	15.65	10.49	17.09	5.80	8.60
Same vehicle life	2.92	4.40	4.53	6.36	2.97	4.57	2.09	2.87
20% longer vehicle life	2.44	3.68	3.51	6.62	2.17	3.56	1.65	2.83
No limit on shelf life	2.63	3.59	4.19	5.33	1.37	2.71	1.82	2.27
10% less power	2.33	3.67	3.85	6.10	2.46	3.85	1.60	2.60
Break-even, Escort (*$/gal*)								
Base case	3.27	4.84	5.04	7.73	3.38	5.06	2.40	3.59
Highway cycle	4.50	6.37	7.20	10.64	4.83	7.15	3.36	4.99
Low-volume production	7.41	10.12	11.95	17.96	12.47	19.61	7.33	10.33
Same vehicle life	3.62	5.11	5.42	7.35	3.66	5.32	2.73	3.53
20% longer vehicle life	3.06	4.34	4.32	7.68	2.74	4.20	2.20	3.46
10% less power	2.98	4.39	4.68	7.14	3.07	4.57	2.19	3.28

[a] See the text for discussion of the scenarios. "Break-even" is the break-even price of gasoline, in 1997 $/gal.

Table 4
Sensitivity of retail and lifecycle cost to the type of drivetrain[a]

Drivetrain	ETX-I AC induction		ETX-II Permanent magnet		Hughes G50 AC induction		TB-1 Eaton AC induction		GE MEV AC induction	
Range (mi)	100	190	100	190	100	190	100	190	100	190
Retail cost ($)	27,058	33,465	25,837	30,449	26,063	30,906	27,111	33,885	25,452	29,699
Break-even ($/gal)	2.39	4.12	1.95	3.14	2.03	3.28	2.42	4.27	1.82	2.91
Energy use (mi/kWh)	2.47	2.02	3.05	2.65	3.02	2.60	2.34	1.87	3.28	2.86

[a] Results are for the Ford Taurus over the FUDS with NiMH Gen4 battery.

ranges. In all other cases, the high lifecycle cost per mile of the battery dominates all other lifecycle cost differences between the BPEV and ICEV, and causes the BPEV to have a comparatively high lifecycle cost and break-even price (see also the "lifecycle cost summary" detailed tables in

Appendix A). It is important to note, though, that the characterization of the NiMH Gen4 battery (and the Li-ion battery, for that matter) is much more speculative than is the characterization of the Pb/acid and NiMH Gen2 batteries. The NiMH Gen4 case should be viewed as something akin to a "best battery" scenario.

As shown in the detailed tables in Appendix A, the BPEVs have somewhat lower M&R, oil, and inspection costs, and, if they use off-peak power, lower energy costs as well. However, most or all of this lower cost per mile is offset by higher insurance costs per mile, due to the higher value of the BPEV (due, in turn, to the high cost of the battery), plus the additional cost of the home recharging station ($1200, $800, and $400 in the respective low, medium, and high production volume cases), plus the cost of propane for cabin heating, plus in some cases slightly higher registration costs.[10] Thus, differences in vehicle operating costs per mile tend to cancel, and overall do not figure prominently in the final lifecycle cost results. The lifecycle cost comparison comes down to the lifecycle cost of the battery.

The two cases shown above in which the break-even gasoline price is less than $2 per gallon nicely illustrate the working of the model and the importance of cost parameters related to the battery. The Ford Taurus with a 70 or 100 mile range on a NiMH Gen4 battery has a relatively low lifecycle cost because the cost per mile of the battery is considerably lower than in other cases. The battery cost per mile is low in part because the vehicle has a short range and because the battery has relatively high specific energy and relatively low manufacturing cost, but also because the battery lasts for more than half the life of the vehicle. Furthermore, the relatively low weight of the battery reduces the weight of the vehicle and thereby reduces fuel, tire, and registration costs. Also, the relatively low cost (and hence replacement value) of the battery reduces the cost of insurance. It takes all of these favorable interactions in order to produce a break-even gasoline price of under $2 per gallon.

5.4. Sensitivity analyses

In this section, the impacts on cost of varying some key parameters away from their base–case values are examined. These key parameters include the assumed driving cycle, vehicle production level, battery life parameters, assumed vehicle life, parameters that affect vehicle efficiency, and several other more minor factors.

Highway cycle. First, there are potentially important impacts of designing the BPEVs to satisfy the range requirement over the highway cycle rather than the FUDS. In almost all cases, the initial cost of a BPEV designed to the highway cycle is lower than for a BPEV designed to the FUDS. This is because BPEVs are about 10% more efficient in highway than in city driving. This is due to the fact that in highway driving the drivetrain operates less often at low torque and low rpm, which is a relatively inefficient combination. The increase in efficiency decreases the amount of battery-storage energy – and hence battery cost – required to supply the desired range.

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[10] Since BPEVs are estimated to be more expensive to purchase than comparable ICEVs, people may be more careful with them. This may ultimately translate into lower insurance rates, but since this is speculative we do not quantify this potential effect. In general our assumptions for insurance rates are for high volume production; when BPEVs are novel and scarce their insurance rates may not be the same as then they are produced in high volumes.

However, even though the *difference* in cents/mile lifecycle cost decreases slightly over the highway cycle than over the FUDS, the break-even gasoline price increases substantially compared to that over the FUDS. This is because the fuel economy of the gasoline Taurus is much higher in the highway than in the city cycle (32 versus 20 mpg), and a higher ICEV fuel economy requires a higher break-even gasoline price to cover any given "cents per mile" difference between the BPEV and ICEV. In the calculation of the break-even price, the effect of the increase in ICEV fuel economy effect outweighs the slight reduction in lifecycle cents per mile.

Production level. The initial and lifecycle costs of low-volume production are much higher than those for high-volume production. As shown in Table 3 (above), break-even gasoline prices at least double, and initial retail costs increase by ten thousand dollars or more.

Battery calendar ("shelf") life and salvage value. A key point is that the battery shelf life and calendar life turn out to be critical parameters, because in many cases the battery reaches the end of its calendar life before it reaches the end of its cycle life. If the calendar life limit is relaxed, so that the cycle life is the determining factor, the break-even gasoline prices are substantially reduced in all of the higher range cases.

The calendar life is estimated to be up before the cycle life when the driving range is longer because of the greater time between cycles, due to the longer driving distance between cycles. In the case of Li/ion, the relaxation of calendar life greatly reduces the break-even price, because of the very high projected cycle life (which now becomes the determining parameter). Thus, if Li/ion batteries can be designed to last at least the life of the motor vehicle, with the cost and performance characteristics assumed here, then BPEVs that use them may have lifecycle costs competitive with those of gasoline ICEVs.

In Delucchi (2000a), arguments are mentioned (but not accepted) that NiMH batteries salvaged from motor vehicles might have a relatively high value in stationary applications. [11] If in fact the NiMH battery has a salvage value of, for example, \$100/kWh, then the break-even gasoline price declines by about \$0.10/gal.

Vehicle lifetime. Relatively small changes in the assumed lifetime VMT of the BPEV (exclusive of the lifetime of the battery, drivetrain, and fuel cell, which are treated separately) can be important to the lifecycle cost. In the base case, the BPEV has a 10% longer VMT lifetime than does the ICEV. If this advantage is eliminated, so that the lifetime of the BPEV is the same as the lifetime of the ICEV, the break-even price in most cases increases by 5–10%. However, in a few cases, the shorter lifetime actually decreases the break-even gasoline price, most likely because in some cases shortening the vehicle life forestalls a relatively costly battery replacement. [12] Conversely, a further increase in the life of the BPEV, to 20% longer than that of the ICEV, generally decreases the break-even price. In a few cases, however, the longer life results in a higher break-even price, because the vehicle owner must make an additional battery purchase.

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[11] We are skeptical of this, because in our analysis, the battery is scrapped when it has lost 40% of its capacity, and at that point it is losing remaining capacity quickly.

[12] Because the salvage value of a used battery is relatively low, it is more cost-effective for the last battery to die about when the vehicle dies than to have to salvage a relatively good battery from a scrapped vehicle. If the increase in vehicle life forces a last-minute battery replacement, the lifecycle cost will increase, because that expensive additional battery will be used for only a few thousand miles before it is salvaged at a relatively low value when the vehicle finally dies.

Drivetrain efficiency and power. Parameters that effect the energy use of the BPEV have a significant effect on the retail cost and break-even gasoline price, because the energy use determines the amount of battery needed to supply a given range. In the vehicle performance model and that underlies this analysis, there are torque/rpm efficiency maps for five different motor/controller sets. The differences in these maps result in significant differences in the overall energy consumption of the vehicle. These differences in energy consumption translate directly into significant differences in the cost of the battery, and hence the retail cost of the vehicle and the lifecycle break-even gasoline price (Table 4).

The base–case motor/controller set, the GE MEV, is the most efficient, and produces the lowest initial and lifecycle costs (Table 4). With the GE MEV set rather than the least efficient set (the TB-1 Eaton), the BPEV is much more efficient, costs $1700–$4200 less (with driving ranges of 100–190 miles), and has a much lower break-even gasoline price.

In the base case, the BPEV has the same performance as the ICEV. If one relaxes the performance requirement a little, so that the BPEV has 90% of the maximum power of the ICEV, then the battery and drivetrain can have a lower maximum power. The reduction in the maximum power allows the battery to be designed for a higher specific energy, which ultimately reduces the weight and cost of the battery. This reduction, combined with the reduction in the cost of the powertrain, results in a significant decrease in the initial and lifecycle cost (Table 3).

Air conditioning and heating. The minor use of air conditioning assumed in the base case turns out to have a relatively small effect on vehicle efficiency and lifecycle cost. It reduces vehicle efficiency by about 4%, increases battery weight by about 3%, and increases the break-even gasoline price by about $0.10/gal.

As shown in the lifecycle cost summary tables in Appendix A, assumptions regarding BPEV heating (e.g., that the BPEV is operated 20% of the time in 45°F ambient temperature) result in a non-trivial cost per mile for propane fuel for heating. Indeed, in the base case, the cost per mile of heating fuel is about the same as the tire replacement cost per mile, or the registration cost per mile. And in very cold conditions, such as operation 35% of the time in 30°F weather, the cost of heating fuel is the same as the cost of electricity to power the vehicle! However, the cost of heating the battery itself in cold weather is trivial – it adds only a penny or two to the break-even gasoline price.

Electricity price. In the base case, a relatively low price of electricity is assumed of $0.06 per kWh. This is plausible given the time-of-use rate plans available to customers of some utilities, and the fact that much BPEV recharging should occur off-peak. However, at the national average residential price of about $0.08 per kWh (Energy Information Administration, 2000), the break-even price increases by about $0.16 per gallon, and at $0.10 per kWh, the break-even price increases by about $0.34 per gallon, for the Ford Taurus BPEV.

Small BPEVs. It is possible that so-called "neighborhood electric vehicles" (NEVs), which are small BPEVs with a top speed of 25 mph or less and a driving range of about 35 miles, will have a retail cost very close to that of a comparable gasoline ICE neighborhood vehicle. The battery in a NEV is very small, on account of the very short range and very high efficiency of the vehicle (the high efficiency, in turn, results from the light weight), and hence is relatively inexpensive. If the electric drivetrain scales down more cost effectively than does the ICE drivetrain, then the resultant savings with the electric drivetrain will at least partially offset the relatively small additional cost of the battery. This appears to be an interesting topic for further research.

Table 5
The social cost of battery electric and gasoline passenger cars[a]

Cost item	EV cent/mi minus ICEV cents/mi		
	low cost	high cost	best est.
1. Private ownership and operating costs	2.00	20.00	10.00
2a. Noise	0.00	−0.40	−0.01
2b. Externalities of oil use	−0.20	−1.12	−0.36
2c. Climate change	−0.00	−0.06	−0.03
2d. Air pollution[b]	−0.17	−2.11	−0.69
2. Total external cost difference (2a + 2b + 2c + 2d)	−0.37	−3.69	−1.09
Total social-cost difference (1 + 2)	1.63	16.31	8.91

[a] *Source*: Author estimates, based in part on external cost data reported in Delucchi (1998). See Delucchi (2000b) for a similar table.

[b] In the case of the BPEV, this includes air pollution from remote fossil-fuel power plants.

Social costs. In the introduction to this paper, we suggested that if "BPEVs are much more costly to manufacture and operate than are comparable ICEVs, then society must ask whether the social benefits of BPEVs justify the greater 'private' costs to consumers or producers". In this scenario, estimates of the so-called "external" costs of motor vehicle use are used to shed some light on this question.

Using the marginal external cost figures presented in Delucchi (1998, 2000b), and the private lifecycle costs analyzed here, the social lifecycle costs of BPEVs can be compared with those of gasoline ICEVs. [13] Table 5 shows that a gasoline ICEV does have greater external costs than does a BPEV, but that these differences probably are much smaller than the difference in the private ownership and operating cost. The cost per mile of the BPEV battery, even under high-volume, "learned-out" production, is higher than the relatively small reductions in air pollution and oil use externalities – which are small in part because modern gasoline vehicles are relatively clean and efficient. [14]

Kazimi (1997) and Funk and Rabl (1999) have reached a similar conclusion regarding BPEVs. Using a dynamic micro-simulation model to investigate vehicle demand and usage as alternative-fuel vehicles are introduced into the market, Kazimi (1997) finds that the cost of mandates that require the introduction of BPEVs may exceed the health benefits of reduced air pollution. [15] Funk and Rabl (1999) use damage-cost estimates from the European "ExternE" project to compare the social costs and benefits of EVs and conventional vehicles in France. They find that even in Paris, where exposure to vehicle emissions is high, the social cost of BPEVs is significantly higher than the social cost of gasoline vehicles.

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[13] Note again that the social cost figure does not include the consumer value of differences in vehicle range and performance, refueling, handling, design, and so on.

[14] This conclusion might not apply to electric vehicles powered by fuel cells, or to very small "neighborhood" electric vehicles (due to their lower battery costs).

[15] Although Kazimi does not consider all of the environmental or energy benefits of EVs, neither does she consider all of the costs of the zero-emission vehicle mandate.

6. Conclusions

Battery manufacturing costs and the parameters that affect battery lifecycle costs, such as the battery calendar life and cycle life (which is related to driving and recharging patterns), are the most important parameters in the BPEV cost analysis. The high cost of the battery increases the initial cost of the vehicle, and also increases the insurance and registration costs. Battery initial and replacement costs are a significant component of the total lifecycle cost of BPEVs.

This analysis suggests that in order for BPEVs to be cost-competitive with gasoline ICEVs, batteries will have to better than the best batteries analyzed here. They will have to have a lower manufacturing cost, and a longer life, than the Li/ion and NiMH batteries analyzed. We believe that it is most important to reduce the manufacturing cost to $100/kWh or less (this will result in a retail-level cost of under $200/kWh), [16] attain a cycle life of 1200 or more cycles and a calendar life of 12 years or more, and aim for a specific energy of around 100 Wh/kg. These cost and life targets are the same as the long-term cost and life goals of the US advanced battery consortium (USABC), but the specific energy target actually is much less than the USABC long-term goal of 200 Wh/kg and commercialization goal of 150 Wh/kg.

Because at the moment there are no prospects for achieving such high energy densities at low cost, it may be a mistake to continue to focus efforts on attaining very high specific energy in order to supply a long driving range. It may well be better to aim for a modest range of no more than 100 miles, [17] and focus then on reducing the manufacturing cost and improving the cycle life of the battery technologies that can offer this range. In the analyses of lifecycle cost as a function of driving range (shown in the tables in the Appendix A), the lifecycle cost increases with driving range with the result that BPEVs with a 150 + mile range have a much higher lifecycle cost than do comparable gasoline ICEVs, at gasoline prices expected to prevail for at least two decades. However, in a few cases, a very short driving range, combined with favorable values for other parameters, result in a nearly competitive lifecycle cost for BPEVs.

This approach suggests that BPEVs may be more likely to be successful as niche-market products, rather than as replacements for the majority of ICEVs in service. However, even short-range BPEVs can provide significant environmental and social benefits by displacing short trips by ICEVs, for households or commercial fleets where short trips are common and where some percentage of the vehicles in the fleet can be of limited range. Based on our analysis of the costs of BPEVs, we believe that hybrid and fuel cell EVs may be more suitable replacements for conventional vehicles in general, given overall cost and marketability factors. We suggest continued analysis of the manufacturing, lifecycle, and social costs of all of these vehicle alternatives, to help to identify the best strategies for reducing pollutant and greenhouse gas emissions, and other negative social and environmental impacts associated with motor vehicle use.

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[16] If the ratio of the retail to the manufacturing cost is less than we have estimated here, then the competitive battery manufacturing cost is greater than $100/kWh. This ratio is an important uncertainty in our analysis.

[17] For a new battery pack and for a vehicle tested over the FUDS cycle. “Real world” driving range is likely to be lower.

Table 6
Vehicle characteristics (Ford Taurus, Pb/acid, high volume, FUDS)[a]

Item	Gasoline	BPEV-50	BPEV-65	BPEV-80	BPEV-95	BPEV-110	BPEV-125
Type of traction battery	n.a.[b]	Lead/acid					
Type of motor	n.a.[b]	GE MEV ac induction motor					
Type of motor controller	n.a.[b]	GE MEV inverter					
Maximum power deliverable to wheels (kW)[c]	103	74	82	91	103	116	134
Acceleration from 0 to 60 mph, 0% grade (s)	9.30	9.31	9.31	9.32	9.31	9.30	9.28
Battery cycle life to 80% DoD	n.a.[b]	777	777	777	777	777	777
Battery system specific energy (Wh/kg)	n.a.[b]	33	35	36	37	38	39
Battery contribution to retail cost ($/kWh)	n.a.[b]	294	259	235	217	202	190
Volume of battery/fuel-storage/ fuel-cell system (L)	65	154	206	265	335	419	524
Vehicle life (km)	241,350	265,485	265,485	265,485	265,485	265,485	265,485
Weight of the complete vehicle (kg)	1416	1463	1635	1835	2069	2354	2710
Weight of battery/fuel-storage/ fuel-cell system (kg)	n.a.[b]	360	475	610	770	965	1,214
Coefficient of drag	0.30	0.24	0.24	0.24	0.24	0.24	0.24
Energy efficiency, mi/kWh from the outlet	n.a.[b]	2.79	2.61	2.41	2.22	2.02	1.81
Fuel economy (gasoline-equivalent mpg, HHV)[d]	19.9	102.2	95.5	88.4	81.3	73.9	66.2
Fuel economy (gasoline equivalent liters/100 km)	11.8	2.3	2.5	2.7	2.9	3.2	3.6
Powertrain efficiency ratio[e]	n.a.[b]	7.97	7.37	6.77	6.19	5.61	5.01

[a] In all column headings, BPEV-xxx means "battery-powered electric vehicle with a range of xxx miles".

[b] n.a. = not applicable.

[c] Maximum power assumes no air conditioning or heating or optional accessories.

[d] Fuel economy of BPEVs is based on electricity from the outlet.

[e] The ratio of mi/BTU-from-battery to mi/BTU-gasoline.

Table 7
Cost summary (Ford Taurus, Pb/acid, high volume, FUDS)

Item	Gasoline	BPEV-50	BPEV-65	BPEV-80	BPEV-95	BPEV-110	BPEV-125
Fuel retail cost, excluding taxes ($/gasoline-equivalent gallon)	0.90	2.20	2.20	2.20	2.20	2.20	2.20
Full retail cost of vehicle, incl. taxes ($)	20,085	23,363	24,553	25,918	27,510	29,422	31,814
Battery contribution to retail cost ($)	n.a.[a]	3447	4276	5190	6231	7447	8940
Levelized maintenance cost ($/yr)	492	355	355	355	355	355	355
Total lifecycle cost (*cents/mile*)	38.71	44.77	45.55	46.39	49.37	53.11	57.92
Present value of lifecycle cost versus gasoline ($)[b]	45,892	10,516	11,495	12,556	16,305	21,018	27,072
Break-even gasoline price ($/gal)	n.a.[a]	2.48	2.64	2.80	3.40	4.14	5.09

[a] n.a. = not applicable.

[b] For gasoline, the present value is shown. For the BPEVs, the difference between the present value for the BPEV and the present value for gasoline is shown.

Table 8
Lifecycle cost summary (Ford Taurus, Pb/acid, high volume, FUDS) (US cents/mile)

Cost item	Gasoline	BPEV-50	BPEV-65	BPEV-80	BPEV-95	BPEV-110	BPEV-125
Independently calculated cost of fast recharging	n.a.[a]	0.00	0.00	0.00	0.00	0.00	0.00
Purchased electricity (including battery heating, if any)	n.a.[a]	2.15	2.30	2.49	2.70	2.97	3.32
Vehicle, excluding battery[b]	17.55	16.38	16.73	17.15	17.67	18.33	19.19
Battery and tray and auxiliaries[b]	n.a.[a]	10.03	9.84	9.66	11.30	13.53	16.29
Space heating fuel for BPEVs	0.00	0.53	0.53	0.53	0.53	0.52	0.52
Motor fuel, excluding excise taxes and electricity	4.52	0.00	0.00	0.00	0.00	0.00	0.00
Home battery-recharging station	n.a.[a]	0.22	0.22	0.22	0.22	0.22	0.22
Insurance (calculated as a function of VMT and vehicle value)	6.75	7.26	7.54	7.86	8.24	8.68	9.24
Maintenance and repair, excluding oil, inspection, cleaning, towing	4.88	3.72	3.72	3.72	3.72	3.72	3.72
Engine oil	0.17	0.00	0.00	0.00	0.00	0.00	0.00
Replacement tires (calculated as a function of VMT and vehicle weight)	0.50	0.46	0.60	0.62	0.76	0.79	0.94
Parking, tolls, and fines (assumed to be the same for all vehicles)	1.05	1.05	1.05	1.05	1.05	1.05	1.05
Registration fee (calculated as a function of vehicle weight)	0.50	0.54	0.61	0.68	0.77	0.87	1.00
Vehicle safety and emissions inspection fee	0.60	0.21	0.21	0.21	0.21	0.21	0.21
Federal, state, and local fuel (energy) excise taxes	1.90	1.90	1.90	1.90	1.90	1.90	1.90
Accessories (assumed to be the same for all vehicles)	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Total lifecycle cost (*cents/mile*)	38.71	44.77	45.55	46.39	49.37	53.11	57.92
The break-even price of gasoline, including taxes	n.a.[a]	2.48	2.64	2.80	3.40	4.14	5.09

[a] n.a. = not applicable.
[b] Retail-cost equivalent.

Table 9
Vehicle characteristics (Ford Taurus, NiMH Gen2, high volume, FUDS)

Cost item	Gasoline	BPEV-65	BPEV-90	BPEV-115	BPEV-140	BPEV-165	BPEV-190
Type of traction battery	n.a.[a]	Nickel metal hydride, generation 2					
Type of motor	n.a.[a]	GE MEV ac induction motor					
Type of motor controller	n.a.[a]	GE MEV inverter					
Maximum power deliverable to wheels (kW)[b]	103	63	69	75	82	90	100
Acceleration from 0 to 60 mph, 0% grade (s)	9.30	9.34	9.32	9.29	9.30	9.29	9.29
Battery cycle life to 80% DoD	n.a.[a]	666	666	666	666	666	666
Battery system specific energy (Wh/kg)	n.a.[a]	67	71	73	75	77	79
Battery contribution to retail cost ($/kWh)	n.a.[a]	551	475	428	389	361	338
Volume of battery/fuel-storage/ fuel-cell system (L)	65	77	105	137	175	218	269
Vehicle life (km)	241,350	265,485	265,485	265,485	265,485	265,485	265,485
Weight of the complete vehicle (kg)	1416	1246	1361	1489	1638	1809	2011
Weight of battery/fuel-storage/ fuel-cell system (kg)	n.a.[a]	208	288	380	479	597	734
Coefficient of drag	0.30	0.24	0.24	0.24	0.24	0.24	0.24
Energy efficiency, mi/kWh from the outlet	n.a.[a]	2.48	2.39	2.28	2.15	2.02	1.87
Fuel economy (gasoline-equivalent mpg, HHV)[c]	19.9	91.0	87.5	83.6	78.8	73.9	68.5
Fuel economy (gasoline equivalent liters/100 km)	11.8	2.6	2.7	2.8	3.0	3.2	3.4
Powertrain efficiency ratio[d]	n.a.[a]	8.78	8.31	7.86	7.33	6.83	6.30

[a] n.a. = not applicable.

[b] Maximum power assumes no air conditioning or heating or optional accessories.

[c] Fuel economy of BPEVs is based on electricity from the outlet.

[d] The ratio of mi/BTU-from-battery to mi/BTU-gasoline.

Table 10
Cost summary (Ford Taurus, NiMH Gen2, high volume, FUDS)

Cost item	Gasoline	BPEV-65	BPEV-90	BPEV-115	BPEV-140	BPEV-165	BPEV-190
Fuel retail cost, excluding taxes ($/gasoline-equivalent gallon)	0.90	2.20	2.20	2.20	2.20	2.20	2.20
Full retail cost of vehicle, incl. taxes ($)	20,085	25,984	28,034	30,261	32,834	35,759	39,223
Battery contribution to retail cost ($)	n.a.[a]	7,651	9,675	11,809	14,063	16,603	19,488
Levelized maintenance cost ($/yr)	492	355	355	355	355	355	355
Total lifecycle cost (cents/mile)	38.71	51.49	53.39	55.36	60.14	65.77	72.53
Present value of lifecycle cost versus gasoline ($)[b]	45,892	18,982	21,369	23,858	29,878	36,974	45,484
Break-even gasoline price ($/gal)	n.a.[a]	3.82	4.19	4.59	5.54	6.66	8.00

[a] n.a. = not applicable.

[b] For gasoline, the present value is shown. For the BPEVs, the difference between the present value for the BPEV and the present value for gasoline is shown.

Table 11
Lifecycle cost summary (Ford Taurus, NiMH Gen2, high volume, FUDS) (US cents/mile)[a]

Cost item	Gasoline	BPEV-65	BPEV-90	BPEV-115	BPEV-140	BPEV-165	BPEV-190
Independently calculated cost of fast recharging	n.a.[a]	0.00	0.00	0.00	0.00	0.00	0.00
Purchased electricity (including battery heating, if any)	n.a.[a]	2.42	2.51	2.63	2.79	2.97	3.21
Vehicle, excluding battery[b]	17.55	15.20	15.30	15.46	15.83	16.28	16.91
Battery and tray and auxiliaries[b]	n.a.[a]	17.16	18.32	19.44	22.90	27.15	32.02
Space heating fuel for BPEVs	0.00	0.54	0.53	0.53	0.53	0.53	0.53
Motor fuel, excluding excise taxes and electricity	4.52	0.00	0.00	0.00	0.00	0.00	0.00
Home battery-recharging station	n.a.[a]	0.22	0.22	0.22	0.22	0.22	0.22
Insurance (calculated as a function of VMT and vehicle value)	6.75	7.88	8.36	8.88	9.47	10.15	10.96
Maintenance and repair, excluding oil, inspection, cleaning, towing	4.88	3.72	3.72	3.72	3.72	3.72	3.72
Engine oil	0.17	0.00	0.00	0.00	0.00	0.00	0.00
Replacement tires (calculated as a function of VMT and vehicle weight)	0.50	0.44	0.45	0.47	0.60	0.62	0.76
Parking, tolls, and fines (assumed to be the same for all vehicles)	1.05	1.05	1.05	1.05	1.05	1.05	1.05
Registration fee (calculated as a function of vehicle weight)	0.50	0.46	0.50	0.55	0.61	0.67	0.75
Vehicle safety and emissions inspection fee	0.60	0.21	0.21	0.21	0.21	0.21	0.21
Federal, state, and local fuel (energy) excise taxes	1.90	1.90	1.90	1.90	1.90	1.90	1.90
Accessories (assumed to be the same for all vehicles)	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Total lifecycle cost (*cents/mile*)	38.71	51.49	53.39	55.36	60.14	65.77	72.53
The break-even price of gasoline, including taxes	n.a.[a]	3.82	4.19	4.59	5.54	6.66	8.00

[a] n.a. = not applicable.

[b] Retail-cost equivalent.

Table 12
Manufacturing cost and weight (Ford Taurus, NiMH Gen2, high volume, FUDS)[a]

Baseline vehicle components	Manufacturing costs ($)			Weight (lbs)		
	ICEV	BPEV-90	BPEV-165	ICEV	BPEV-90	BPEV-165
Body, chassis, interior, electrical, steering, etc.	3621	3566	3872	2080	2044	2243
Powertrain, emission control, brakes, fluids[b]	2468	3016	3700	1141	374	496
Vehicle assembly (excl. battery, fuel tank)	1715	1458	1458	n.a.[c]	n.a.[c]	n.a.[c]
Traction battery	0	5132	9589	0	579	1211
Traction battery auxiliaries	0	69	124	0	59	104
Final assembly of battery and fuel tanks	0	74	74	n.a.[d]	n.a.[c]	n.a.[c]
Adjustments to baseline (v. 1989)						
Air conditioning, BPEV heater, thermal management (incl. assembly)	400	850	850	70	110	110
Improved emission control system	150	0	0	15	0	0
New safety features (except air bags)	100	100	100	40	40	40
Engine and transmission improvements	200	0	0	(80)	0	0
Body weight-reduction measures	140	200	200	(250)	(371)	(371)
Drag-reduction measures	20	50	50	0	0	0
Subtotal manufacturing costs	8814	14,515	20,016	n.a.[c]	n.a.[c]	n.a.[c]
Division costs (engineers, testing, advertising)	4162	4969	5749	n.a.[c]	n.a.[c]	n.a.[c]
Corporate costs (executives, capital, R & D)	2166	2329	2487	n.a.[c]	n.a.[c]	n.a.[c]
Corporate cost of money	222	320	415	n.a.[c]	n.a.[c]	n.a.[c]
Corporate true profit (taken as fraction of factory invoice)	475	684	884	n.a.[c]	n.a.[c]	n.a.[c]
Factory invoice (price to dealer)	15,840	22,815	29,479	n.a.[c]	n.a.[c]	n.a.[c]
Dealer costs	3177	3928	4645	n.a.[c]	n.a.[c]	n.a.[c]
Manufacturers' suggested retail price (MSRP)	19,017	26,743	34,124	n.a.[c]	n.a.[c]	n.a.[c]
Shipping cost	483	454	613	n.a.[c]	n.a.[c]	n.a.[c]
Other costs	0	0	0	n.a.[c]	n.a.[c]	n.a.[c]
Final retail cost and weight						
Consumer cost = MSRP + shipping+ tax ($)[d]	20,085	28,013	35,780	n.a.[c]	n.a.[c]	n.a.[c]
Curb weight (no payload, full fuel)(lbs)	n.a.[c]	n.a.[c]	n.a.[c]	3016	2835	3831
Actual in-use weight (lbs)	n.a.[c]	n.a.[c]	n.a.[c]	3122	3000	3990

[a] Note that there are slight discrepancies between the costs and weights shown here, and the values shown in the vehicle characteristics and cost summary tables, on account of slightly different resolutions of the circularities in the model, in different model runs.

[b] The fuel tank is 40% full in the weight and energy-use analysis, empty in the cost analysis.

[c] n.a. = not applicable.

[d] Retail price includes license fees and all mark-ups and taxes.

Table 13
Vehicle characteristics (Ford Taurus, Li/ion, high volume, FUDS)

Cost item	Gasoline	BPEV-100	BPEV-140	BPEV-180	BPEV-220	BPEV-260	BPEV-300
Type of traction battery	n.a.[a]	Lithium/ion					
Type of motor	n.a.[a]	GE MEV ac induction motor					
Type of motor controller	n.a.[a]	GE MEV inverter					
Maximum power deliverable to wheels (kW)[b]	103	60	64	69	73	79	84
Acceleration from 0 to 60 mph, 0% grade (s)	9.30	9.32	9.32	9.29	9.30	9.29	9.30
Battery cycle life to 80% DoD	n.a.[a]	1110	1110	1110	1110	1110	1110
Battery system specific energy (Wh/kg)	n.a.[a]	118	129	136	143	147	152
Battery contribution to retail cost ($/kWh)	n.a.[a]	416	337	289	253	228	207
Volume of battery/fuel-storage/ fuel-cell system (L)	65	93	125	158	196	235	281
Vehicle life (km)	241,350	265,485	265,485	265,485	265,485	265,485	265,485
Weight of the complete vehicle (kg)	1416	1189	1273	1362	1462	1567	1686
Weight of battery/fuel-storage/ fuel-cell system (kg)	n.a.[a]	172	229	294	359	432	512
Coefficient of drag	0.30	0.24	0.24	0.24	0.24	0.24	0.24
Energy efficiency, mi/kWh from the outlet	n.a.[a]	4.17	3.99	3.82	3.62	3.44	3.25
Fuel economy (gasoline-equivalent mpg, HHV)[c]	19.9	152.8	146.0	139.9	132.4	125.9	119.0
Fuel economy (gasoline equivalent liters/100 km)	11.8	1.5	1.6	1.7	1.8	1.9	2.0
Powertrain efficiency ratio[d]	n.a.[a]	9.11	8.73	8.39	7.96	7.59	7.19

[a] n.a. = not applicable.

[b] Maximum power assumes no air conditioning or heating or optional accessories.

[c] Fuel economy of BPEVs is based on electricity from the outlet.

[d] The ratio of mi/BTU-from-battery to mi/BTU-gasoline.

Table 14
Cost summary (Ford Taurus, Li/ion, high volume, FUDS)

Cost item	Gasoline	BPEV-100	BPEV-140	BPEV-180	BPEV-220	BPEV-260	BPEV-300
Fuel retail cost, excluding taxes ($/gasoline-equivalent gallon)	0.90	2.20	2.20	2.20	2.20	2.20	2.20
Full retail cost of vehicle, incl. taxes ($)	20,085	26,135	27,678	29,174	30,791	32,448	34,268
Battery contribution to retail cost ($)	n.a.[a]	8430	10,000	11,513	12,993	14,516	16,121
Levelized maintenance cost ($/yr)	492	355	355	355	355	355	355
Total lifecycle cost (cents/mile)	38.71	43.55	46.22	48.70	51.34	54.06	57.16
Present value of lifecycle cost versus gasoline ($)[b]	45,892	8,974	12,339	15,463	18,791	22,210	26,115
Break-even gasoline price ($/gal)	n.a.[a]	2.24	2.77	3.26	3.79	4.33	4.94

[a] n.a. = not applicable.

[b] For gasoline, the present value is shown. For the BPEVs, the difference between the present value for the BPEV and the present value for gasoline is shown.

Table 15
Lifecycle cost summary (Ford Taurus, Li/ion, high volume, FUDS) (US cents/mile)

Cost item	Gasoline	BPEV-100	BPEV-140	BPEV-180	BPEV-220	BPEV-260	BPEV-300
Independently calculated cost of fast recharging	n.a.[a]	0.00	0.00	0.00	0.00	0.00	0.00
Purchased electricity (including battery heating, if any)	n.a.[a]	1.44	1.51	1.57	1.66	1.74	1.85
Vehicle, excluding battery[b]	17.55	14.68	14.72	14.76	14.93	15.11	15.36
Battery and tray and auxiliaries[b]	n.a.[a]	10.82	12.87	14.85	16.81	18.83	20.98
Space heating fuel for BPEVs	0.00	0.54	0.53	0.53	0.53	0.53	0.53
Motor fuel, excluding excise taxes and electricity	4.52	0.00	0.00	0.00	0.00	0.00	0.00
Home battery-recharging station	n.a.[a]	0.22	0.22	0.22	0.22	0.22	0.22
Insurance (calculated as a function of VMT and vehicle value)	6.75	7.91	8.27	8.62	9.00	9.38	9.81
Maintenance and repair, excluding oil, inspection, cleaning, towing	4.88	3.72	3.72	3.72	3.72	3.72	3.72
Engine oil	0.17	0.00	0.00	0.00	0.00	0.00	0.00
Replacement tires (calculated as a function of VMT and vehicle weight)	0.50	0.32	0.45	0.45	0.46	0.47	0.61
Parking, tolls, and fines (assumed to be the same for all vehicles)	1.05	1.05	1.05	1.05	1.05	1.05	1.05
Registration fee (calculated as a function of vehicle weight)	0.50	0.44	0.47	0.51	0.54	0.58	0.63
Vehicle safety and emissions inspection fee	0.60	0.21	0.21	0.21	0.21	0.21	0.21
Federal, state, and local fuel (energy) excise taxes	1.90	1.90	1.90	1.90	1.90	1.90	1.90
Accessories (assumed to be the same for all vehicles)	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Total lifecycle cost (*cents/mile*)	38.71	43.55	46.22	48.70	51.34	54.06	57.16
The break-even price of gasoline, including taxes	n.a.[a]	2.24	2.77	3.26	3.79	4.33	4.94

[a] n.a. = not applicable.
[b] Retail-cost equivalent.

Table 16
Vehicle characteristics (Ford Taurus, NiMH Gen4, high volume, FUDS)

Cost item	Gasoline	BPEV-70	BPEV-100	BPEV-130	BPEV-160	BPEV-190	BPEV-220
Type of traction battery	n.a.[a]	Nickel metal hydride, generation 4					
Type of motor	n.a.[a]	GE MEV ac induction motor					
Type of motor controller	n.a.[a]	GE MEV inverter					
Maximum power deliverable to wheels (kW)[b]	103	59	63	67	72	77	83
Acceleration from 0 to 60 mph, 0% grade (s)	9.3	9.32	9.31	9.29	9.29	9.29	9.29
Battery cycle life to 80% DoD	n.a.[a]	1331	1331	1331	1331	1331	1331
Battery system specific energy (Wh/kg)	n.a.[a]	95	103	106	111	114	116
Battery contribution to retail cost ($/kWh)	n.a.[a]	413	336	290	256	231	212
Volume of battery/fuel-storage/ fuel-cell system (L)	65	53	74	96	121	148	178
Vehicle life (km)	241,350	265,485	265,485	265,485	265,485	265,485	265,485
Weight of the complete vehicle (kg)	1416	1156	1238	1326	1425	1533	1653
Weight of battery/fuel-storage/ fuel-cell system (kg)	n.a.[a]	149	206	269	335	409	491
Coefficient of drag	0.30	0.24	0.24	0.24	0.24	0.24	0.24
Energy efficiency, mi/kWh from the outlet	n.a.[a]	3.36	3.25	3.15	3.00	2.87	2.73
Fuel economy (gasoline-equivalent mpg, HHV)[c]	19.9	123.0	119.1	115.2	109.9	105.0	99.9
Fuel economy (gasoline equivalent liters/100 km)	11.8	1.9	2.0	2.0	2.1	2.2	2.4
Powertrain efficiency ratio[d]	n.a.[a]	9.25	8.87	8.52	8.09	7.69	7.29

[a] n.a. = not applicable.

[b] Maximum power assumes no air conditioning or heating or optional accessories.

[c] Fuel economy of BPEVs is based on electricity from the outlet.

[d] The ratio of mi/BTU-from-battery to mi/BTU-gasoline.

Table 17
Cost summary (Ford Taurus, NiMH Gen4, high volume, FUDS)

Cost item	Gasoline	BPEV-70	BPEV-100	BPEV-130	BPEV-160	BPEV-190	BPEV-220
Fuel retail cost, excluding taxes ($/gasoline-equivalent gallon)	0.90	2.20	2.20	2.20	2.20	2.20	2.20
Full retail cost of vehicle, incl. taxes ($)	20,085	24,208	25,487	26,771	28,184	29,692	31,348
Battery contribution to retail cost ($)	n.a.[a]	5838	7083	8306	9508	10,759	12,097
Levelized maintenance cost ($/yr)	492	355	355	355	355	355	355
Total lifecycle cost (cents/mile)	38.70	40.88	41.50	42.84	44.82	46.93	49.38
Present value of lifecycle cost versus gasoline ($)[b]	45,881	5625	6404	8093	10,586	13,247	16,331
Break-even gasoline price ($/gal)	n.a.[a]	1.71	1.83	2.10	2.49	2.91	3.40

[a] n.a. = not applicable.

[b] For gasoline, the present value is shown. For the BPEVs, the difference between the present value for the BPEV and the present value for gasoline is shown.

Table 18
Lifecycle cost summary (Ford Taurus, NiMH Gen4, high volume, FUDS) (US cents/mile)

Cost item	Gasoline	BPEV-70	BPEV-100	BPEV-130	BPEV-160	BPEV-190	BPEV-220
Independently calculated cost of fast recharging	n.a.[a]	0.00	0.00	0.00	0.00	0.00	0.00
Purchased electricity (including battery heating, if any)	n.a.[a]	1.79	1.85	1.91	2.00	2.09	2.20
Vehicle, excluding battery[b]	17.55	15.16	15.24	15.34	15.57	15.84	16.17
Battery and tray and auxiliaries[b]	n.a.[a]	7.79	7.82	8.66	9.94	11.28	12.73
Space heating fuel for BPEVs	0.00	0.54	0.54	0.53	0.53	0.53	0.53
Motor fuel, excluding excise taxes and electricity	4.51	0.00	0.00	0.00	0.00	0.00	0.00
Home battery-recharging station	n.a.[a]	0.22	0.22	0.22	0.22	0.22	0.22
Insurance (calculated as a function of VMT and vehicle value)	6.75	7.46	7.76	8.06	8.39	8.74	9.13
Maintenance and repair, excluding oil, inspection, cleaning, towing	4.88	3.72	3.72	3.72	3.72	3.72	3.72
Engine oil	0.17	0.00	0.00	0.00	0.00	0.00	0.00
Replacement tires (calculated as a function of VMT and vehicle weight)	0.50	0.31	0.44	0.45	0.46	0.47	0.60
Parking, tolls, and fines (assumed to be the same for all vehicles)	1.05	1.05	1.05	1.05	1.05	1.05	1.05
Registration fee (calculated as a function of vehicle weight)	0.50	0.43	0.46	0.49	0.53	0.57	0.61
Vehicle safety and emissions inspection fee	0.60	0.21	0.21	0.21	0.21	0.21	0.21
Federal, state, and local fuel (energy) excise taxes	1.90	1.90	1.90	1.90	1.90	1.90	1.90
Accessories (assumed to be the same for all vehicles)	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Total lifecycle cost (*cents/mile*)	38.70	40.88	41.50	42.84	44.82	46.93	49.38
The break-even price of gasoline, including taxes	n.a.[a]	1.71	1.83	2.10	2.49	2.91	3.40

[a] n.a. = not applicable.

[b] Retail-cost equivalent.

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Appendix A. Detailed model output

See Tables 6–18.

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