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Highway Vehicle Electric Drive in the United States: 2009 Status and Issues

Energy Systems Division

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Highway Vehicle Electric Drive in the United States: 2009 Status and Issues

by
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in support of:
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ACRONYMS, ABBREVIATIONS, AND DEFINITIONS

Acronyms and/or Definitions (clustered by topic)

ICE — internal combustion engine - type used in conventional powertrains, either spark ignited (gasoline) or compression ignited (diesel).

DI — direct injection, the most efficient method available of injecting fuel into a cylinder.

FC — fuel cell.

Ni MH — nickel metal hydride (a battery chemistry used in existing hybrid electric vehicles [HEVs] and some past electric vehicles [EVs]).

Li-ion — lithium-ion (a "family" of battery chemistry candidates for future HEVs, plug-in HEVs [PHEVs], and EVs).

SOC — state of charge of a battery pack. Full = 100%, empty 0%.

Electric machine — What are often labeled motors and/or generators are actually capable of operating in either manner – as a motor or a generator. An electric machine can be a motor-generator, or could be constrained to operate only as a generator or motor. In vehicles with electric drive, the electric machines typically can operate both as a motor and a generator.

kWh — kilowatt-hours. Standard measure of energy use by electric vehicles and the electrical portion of energy use by PHEVs.

Fuel consumption — fuel per unit distance moved. The forms presented and used in this document are: gallons per XX miles for diesel and gasoline, kilowatt hours per XX miles for electricity.

UDDS — urban dynamometer driving schedule, 7.5 miles long, and averaging 19.5 mph. This cycle is used for official estimates of corporate average fuel economy, as well as for the U.S. Environmental Protection Agency (EPA) "5-cycle" test to estimate "real-world" fuel consumption for consumer information purposes.

HWY — highway dynamometer driving schedule, 10.3 miles long, averaging 48.2 mph. Only this cycle and the UDDS are used for official estimates of corporate average fuel economy. They are also two of the cycles used in the EPA "5-cycle" test to estimate "real-world" fuel consumption for consumer information purposes.

US06 A dynamometer driving schedule representing aggressive, high-speed driving; 8 miles long, 48.0 mph, but top speed 34% higher than for HWY and maximum acceleration rate 157% greater than for the HWY cycle. Much more aggressive than nearly all U.S. driving. This cycle, broken down into a city and highway portion, is used only in the EPA “5-cycle” test to estimate “real-world” fuel consumption for consumer information purposes.

SC03 A dynamometer driving schedule representing slightly more aggressive driving than the UDDS, averaging 21.5 mph. This cycle is used only in the EPA “5-cycle” test to estimate “real-world” fuel consumption for consumer information purposes.

New window sticker fuel economy (miles per gallon)
A recently developed, weighted average of several driving tests, using information from tests using the UDDS, HWY, US06, and SC03 driving cycles. It is also referred to as the “5-cycle” measurement method. It adds cold (20°F) operation (using the UDDS cycle) and hot operation (95°F) with air conditioning on, using the SC03 cycle. Resulting fuel consumption is higher than the inverse of the old window sticker value(s). Both city and highway values are estimated, as well as a weighted average of the two – the combined cycle. In this document, only fuel consumption, in gallons per 100 miles, are used. This choice is made because it is more easily and directly related to operating costs than are fuel economy (miles per gallon) measures generally used by automotive engineers. The data in gallons per 100 miles is now available on the Web site, www.fueleconomy.gov, at the same location as the new window sticker fuel economy values. The new 5 cycle method better represents fuel use in “real-world” driving than did prior estimates, which were based on only two cycles, the UDDS and Highway Fuel Economy Test (HWFET), run at 75°F.

CV conventional vehicle. Without a modifier, the acronym implies a gasoline ICE in this document.

FWD front-wheel drive.

RWD rear-wheel drive.

4WD four-wheel drive.

GVW gross vehicle weight (vehicle weight plus manufacturers’ recommended maximum load).

CS charge sustaining (the SOC of the battery does not vary significantly; CS is always used in HEVs and used in all types of plug-in HEVs once the battery charge has been depleted).

CD	charge depleting (the SOC of the battery declines until the battery is nearly discharged; CD mode is used after a battery charge in all types of plug-in HEVs and in EVs).
HEV	hybrid electric vehicle (always gasoline in this document). Uses CS operation only.
Micro or “mild” HEV	In practice to date, HEVs assigned one of these modifiers use one electric machine and provide a relatively small portion of total powertrain power. However, there is not a technical limit on share of power that could be provided.
PHEV	plug-in hybrid electric vehicle (always gasoline in this document). After charging, first runs CD, then CS.
PHEVXX	Where “XX” is filled in by the number of kilometers of the vehicle’s all-electric range nominally obtainable on a certification test. The State of California (2007) has specified a test for certification of all-electric range capability, which requires that the vehicle be able to operate all-electrically while meeting the speed and acceleration requirements of the UDDS. Although this designation is not part of any official terminology, it has become common practice in the United States. “XX” defines the distance that can be traveled when a battery is discharged from full to a selected SOC under specified test conditions. FWD and RWD PHEVs discussed in this document have one engine and one or two electric machines in the powertrain, and 4WD HEVs and PHEVs may have more than two electric machines.
Blended CD	Where both battery electricity and fuel-derived mechanical power are used in CD.
GCRHEV	grid-connectable, retrofitted hybrid electric vehicle. The vehicle can charge from a plug and operate in CD mode; however, it operates blended in almost all circumstances. It has too little battery power to run the UDDS via electric power.
GCHEV	A hypothetical original equipment manufacturer (OEM) HEV that can plug in and uses blended CD operation to deplete charge from the battery.
EV	electric vehicle. A vehicle that makes use of battery electricity only to move it. Most EVs have been designed with one electric machine, but could have as many as four, if “wheel motors” are used.
E-REV	Extended-range electric vehicle, although some may also call it a PHEV. General Motors (GM) distinguishes its Volt by using this term. The E-REV also has two electric machines and one engine. Its largest electric machine must be larger than one that is used in a PHEV, where the engine is linked mechanically to the wheels. The E-REV’s key feature is that during charge depletion, it nearly always

operates only on battery electric power. Exceptions may be incorporated for very cold conditions, where battery power can drop dramatically.

Trouble truck
A truck used by utilities to go to the scene of local electric system troubles and repair the problem, if possible. The truck has a long articulated boom and a bucket for a worker to be lifted to the height of distribution system wires (e.g., telephone pole height) to conduct work. The truck often sits for long periods of time, using power to move the worker and equipment where needed. In recently developed PHEV versions, battery electric operation can prevent hours of engine idling.

Series
Drivetrain type dominating the charge-depletion design philosophy of an E-REV. The configuration in an EV is also called series, so it is not surprising that an "extended-range electric vehicle" would depend on the use of the series configuration. No mechanical power goes to the wheels. In the E-REV, two power paths are used (aside from during unpowered deceleration): (1) the engine-to-generator-to-motor path, and (2) the engine-to-generator-to-battery-to–motor path. In a series E-REV, two on-board electric machines are required, while an EV requires only one on-board electric machine. Only electric drive can power the wheels. This system often has no transmission, using only one gear.

Parallel
One electric machine drivetrain now used in the United States for "mild" HEVs. Engine power pathways include (1) engine to electric machine (as generator) to battery and later back to the electric machine (then acting as a motor), or (2) engine to transmission to driveline to wheels. Both the electric drive and mechanical drive, in parallel, can simultaneously power the wheels. This system can use either a manual or automatic transmission.

BAS
belt alternator system. This parallel system is used in the mild HEVs in a few GM vehicles.

IMA
integrated motor assist. This parallel system is used in Honda's mild HEVs.

Split
A very complex system where two electric machines are used to provide a mix of attributes of the series and parallel powertrains. A planetary gear system is used instead of a transmission. The planetary gear system is comparable to an automatic transmission because no manual shifting is involved. Toyota and Ford use this system. The Toyota and Ford hybrids using this system are often called full hybrids.

Dual mode
A system that is similar in complexity to the split system, but with a more traditional automatic transmission. General Motors, DaimlerChrysler, and BMW jointly developed this system. Several General Motors vehicles are currently available with this system, which is also regarded as a full hybrid.

Full HEV	Based on numbers sold, at this time, the term “full” implies the “split” parallel and series hybrid system originally pioneered by Toyota and used by Ford. However, the dual mode system being sold by GM is also rightfully called a full hybrid.
FCV	fuel cell vehicle (powered by compressed hydrogen).
GHG	greenhouse gases (carbon dioxide, methane, and nitrous oxide for the studies cited here).
CTL	A method of converting coal to liquid fuel for transportation use. The fuel referred to can be substituted for diesel fuel but not for gasoline.
FFV	flex-fuel vehicle. Here, vehicles using ICEs equipped to run either on gasoline or a combination of 85% ethanol (i.e., E85) and 15% gasoline (by volume), using only one tank compatible with both fuels or a mix of the two.
V2G	Vehicle-to-grid, a package of technologies that could allow parked PHEVs to be used to back up the grid, or to stabilize fluctuations in electrical load on the grid. Electrons flow from the vehicle back into the grid, perhaps supporting a load several miles distant.
V2H	Vehicle-to-house, a package of technologies that, at a minimum, allow an HEV, PHEV, GCHEV, or EV to provide either backup emergency power or temporarily support predetermined loads in the house in order to accomplish “load shedding” to assist in maintaining electric grid stability.

ACRONYMS AND UNITS OF MEASURE

amp	ampere(s)
ARRA	American Recovery and Reinvestment Act of 2009
ART	Arterial (driving cycle)
ATVMP	Advanced Technology Vehicles Manufacturing Program
BAS	belt alternator system
BEV	battery electric vehicle
CBD	Central Business District (driving cycle)
CD	charge-depleting
CIDI	compression ignition direct injection
COM	commuter (driving cycle)
CS	charge-sustaining
CTL	coal-to-liquid(s)

DOE	U.S. Department of Energy
EDF	Environmental Defense Fund
EISA	Energy Independence and Security Act of 2007
EPA	U.S. Environmental Protection Agency
EPAct	Energy Policy Act of 2005
EPRI	Electric Power Research Institute
eTec	Electric Transportation Engineering Corporation
EV	electric vehicle
EVSE	electric vehicle supply equipment
FAQ	frequently asked question
FC	fuel cell
FFC	full fuel cycle
FFV	flex fuel vehicle
FTP	Federal Test Procedure (for testing of vehicle emissions and fuel use)
GCHEV	grid-connectable HEV
GCRHEV	grid-connectable retrofitted HEV
GHG	greenhouse gas
GVW	gross vehicle weight
HEV	hybrid electric vehicle
HVAC	heating, ventilation, and air conditioning
HWY	highway (driving cycle)
ICE	internal combustion engine
IMA	integrated motor assist (Honda)
kW	kilowatt (a measure of power)
kWh	kilowatt-hour (a measure of energy)
LCA	life cycle analysis
LFP-G	lithium-iron phosphate with graphite anode
Li-ion	lithium-ion
LMO-G	lithium manganese oxide with graphite anode
LMO-TiO	lithium manganese oxide with titanate anode
mpg	miles per gallon
mpgge	miles per gallon gasoline equivalent
mph	miles per hour
NCA-G	nickel-cobalt-aluminum cathode and graphite anode (a lithium-ion chemistry)
NEC	A Japanese corporation that manufactures batteries
NiMH	nickel metal hydride
OEM	original equipment manufacturer

PHEV	plug-in hybrid electric vehicle
R&D	research and development
SAE	Society of Automotive Engineers
SLPB	superior lithium polymer battery
SOC	state of charge
SUV	sport utility vehicle
TDI	turbocharged direct injection
TEPCO	Tokyo Electric Power Company
UDDS	Urban Dynamometer Driving Schedule
V2G	vehicle-to-grid
V2H	vehicle-to-house
ZEV	zero emissions vehicle

HIGHWAY VEHICLE ELECTRIC DRIVE IN THE UNITED STATES: CURRENT STATUS AND ISSUES

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ABSTRACT

The status of electric drive technology in the United States as of early 2010 is documented. Rapidly evolving electric drive technologies discussed include hybrid electric vehicles, multiple types of plug-in hybrid electric vehicles, and battery electric vehicles. Recent trends for hybrids are quantified. Various plug-in vehicles entering the market in the near term are examined. The technical and economic requirements for electric drive to more broadly succeed in a wider range of highway vehicle applications are described, and implications for the most promising new markets are provided. Federal and selected state government policy measures promoting and preparing for electric drive are discussed. Taking these into account, judgment on areas where increased Clean Cities funds might be most productively focused over the next five years are provided. In closing, the request by Clean Cities for opinion on the broad range of research needs providing near-term support to electric drive is fulfilled.

1 INTRODUCTION

This document was based on one of several topical briefing papers on alternative fuel vehicle technology prepared by selected experts for the U.S. Department of Energy Clean Cities Program, to provide input for a five-year strategic plan. As such, the document focuses on the next five years rather than the longer term. Although funds available for the Clean Cities program have increased significantly, funds nevertheless are regarded as scarce, and so priorities must be set. This document covers "electric drive," a term that includes hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and battery electric vehicles (BEVs). Other papers cover various alternative fuels and fuel efficiency. This document also addresses vehicle sizes and purposes, discussing — at least briefly — vehicles of size and weight ranging from two-seat passenger cars to urban buses and "big-rig" heavy-duty combination trucks. Within this range of vehicles, there is an attempt to identify the most promising target markets for Clean Cities' focus over the next five years. Patterns of use — so called "driving cycles" — are critical to the viability of electric drive alternatives. Important considerations are:

- *Frequency of stops* (electric drive allows engines to be shut off when the vehicle stops)
- *Share of time decelerating and rate of deceleration* (on-board electric machines allow "regenerative" braking to capture and store braking energy otherwise lost)

- *Hours of daily use* (electric drive is expensive – the more it is used, the quicker the payoff of initial costs)

- *The kilowatt-hours required for daily use versus feasible battery energy storage* in PHEVs and BEVs for various vehicle classes.

- *Average speed of driving.* As electric drive becomes dominant in a vehicle, the change of vehicle energy use per mile versus average speed is different than that for conventional drive. Energy consumption per mile will be greatest for BEVs when on Interstate highways, while it is highest in congested stop-and-go driving for conventional drive.

- *Vehicle and battery pack exposure to climatic extremes.* Batteries work most efficiently at temperatures where humans are comfortable. In either extreme heat or cold, batteries operate much less efficiently, have less power, and/or deteriorate more rapidly. Cold climates also are accompanied by snowstorms. Resulting increases in road surface rolling resistance can cause a significant reduction of BEV range until roads are cleared of snow.

Another major consideration is the capital costs required to enable the use of plug-in electric drive.

- *Incremental vehicle costs.* Batteries, in particular, add to the cost of a PHEV or BEV. While costs of energy storage (kWh capability of the pack) dominate the costs, power rating (kW) is also an important factor in pushing up the costs of electric drive. Further, for plug-in vehicles, the batteries being developed are based on lithium ion (Li-ion) chemistries, not the nickel metal hydride (NiMH) chemistry now used in hybrids. While it is clear that Li-ion batteries are the wave of the future, even for HEVs, the reality is that there are several candidate chemistries and cell designs that are being considered for use in plug-in electric vehicles. Early production facilities are likely to be in the tens of thousands, or perhaps over one hundred thousand, while the leading manufacturer of NiMH packs, Panasonic, produces about a half a million packs per year. Thus, even though Li-ion chemistries now dominate consumer electronics, they must pass through the costly low-volume, early technology stage before the long-term promise of the chemistry can be realized for plug-in electric drive. During the next five years, considerable subsidies for battery packs are available to deal with this problem.

- *Charge circuit costs.* The lowest costs for charging services will arise when a standard household plug is very close to the PHEV or BEV charge port, and several hours of charging overnight is acceptable to the owner. As the rate of charging desired increases, new charge circuits must be installed. For reasons discussed in the text, the costs of these circuits can increase to thousands of dollars per charge point for “level 2” charging, and tens of thousands for faster, higher-power “level 3” charging. Labor costs become more important than the equipment and wiring costs.

Automakers are well aware of all of these considerations and are accordingly developing strategies for introducing plug-in vehicles. If the expansion of electric drive has begun a steady rise, then the next five years will be the time during which the plug-in feature is added to the electric drive portfolio, following the relatively steady expansion of HEVs over the past decade.

This document uses the knowledge and judgment of only one author, taking into account many (but hardly all) of the public announcements of automakers, utilities, and other organizations with regard to their plans and visions for the near-term expansion of the electric drive portfolio. Taking into account the knowledge of the factors mentioned above, the behavior of the market for electric drive to date (HEVs), and various industry announcements and government and academic research, this document includes recommendations for focus of attention by Clean Cities (and others) over the next five years. Recognizing that Clean Cities benefits from support of industry, government, and academic research, Clean Cities' instructions to authors were to recommend desirable research that would complement the priorities suggested for use of Clean Cities funds. Accordingly, this document closes with the author's research recommendations that are thought to be necessary to ensure uninterrupted expansion of electric drive, taking appropriate advantage of plug-in features to attract a steadily increasing number of consumers.

2 STATE OF ELECTRIC DRIVE VEHICLE TECHNOLOGY

2.1 HYBRIDS (HEVS)

Since the late 1990s, thanks to significant but less-than-hoped-for progress in battery technology, electric drive has captured a small but increasing share of the new light-duty vehicle market in the United States. After a failure of electric vehicles with large battery packs to achieve market success, expansion of electric drive resulted from the emergence of the hybrid electric vehicle (HEV), which uses a relatively small battery pack (1–2 kilowatt-hours [kWh] of electrical storage capability) that uses the nickel metal hydride (NiMH) chemistry. Battery packs contain many "cells." The cells are what consumers normally think of as batteries. Cells are connected to one another within a pack to provide both the power and energy storage needed to meet the design requirements of the vehicle powertrain. The packs also include a control system and may be cooled conductively through metal, by air or liquid, or by using some combination of these methods. For most of today's HEVs, air and conductive cooling are used. For the first-generation Toyota Prius plug-in HEV (PHEV), which has a much smaller battery pack and charge-depleting (CD) range than does the Chevrolet Volt, active (drawing power to circulate coolant) air cooling is used. The Volt's much more powerful and larger battery pack relies on liquid thermal management to actively prevent either hot or cold extremes.

HEV battery packs are not charged from the electric grid. There is no plug on these vehicles. Electricity is generated aboard the vehicle in two ways, and the stored electricity is later retrieved, *primarily* to assist acceleration of the vehicle and secondarily to support cruising at relatively steady speed. The first method of generating electricity on-board is to have the engine drive an electric machine that operates as a generator during times when the engine operates at very high efficiency. The second method is to use "regenerative" braking to turn an electric machine so that it generates electricity, which is deposited in the battery pack. One way to think of the HEV is that it has two on-board methods of generating electricity: one "green" method involving no fossil fuel use (regenerative braking) and the other that does involve fossil fuel use (i.e., gasoline running the engine). HEVs have two key fuel-saving features in that they eliminate (1) engine operation at idle and (2) fuel flow to the engine during deceleration. By shuttling electricity in and out of the battery pack by using clever controls, the HEV sharply and significantly increases the time that the engine operates at high efficiency, while also significantly reducing the number of engine hours of operation.

The addition of battery power creates a number of important opportunities for HEVs and all PHEVs. The first is the ability to start the engine reliably in a fraction of a second. Providing reliable, nearly instantaneous restarts means that the engine does not have to "stand by" with fuel flowing in case the driver decides suddenly and unpredictably to accelerate. At low speeds, the high, instantly available torque of electric motors means that the motor can provide acceleration, while a property of batteries can be used to start the engine almost instantaneously. The property of batteries in question is an ability to provide much higher-than-rated power for a very short time.

As electric power capability rises, the vehicle attains an ability to be driven in an all-electric mode for a larger and larger fraction of driving time, so long as energy is available. With today's full hybrids, if the driver has a "light" foot (accelerates gently) and does not drive too fast, all-electric operation can be accomplished for as long as a mile if the battery has coincidentally been "topped off" (or charged to its allowed maximum) before the driver's effort to achieve all-electric operation. HEVs can often achieve all-electric operation when ending a trip in a neighborhood with a limited legal top speed. In order to use grid electricity *and* drive on urban streets in all-electric mode, still more electrical power (both in the battery and motor) and energy (in the battery) are necessary. However, even without more power, it has been demonstrated by battery manufacturers that batteries storing more energy can be added to today's full hybrids with a plug, and electricity can replace a considerable amount of the gasoline otherwise used until the battery is emptied (Carlson, 2007; Duoba and Carlson, 2007; Idaho National Laboratory, 2009). The less power available in the battery, the less electricity per mile is used, and the longer the time until the battery runs out of its stored energy (depletes).

Another advantage of the relatively high torque of electric motors is that more efficient engine technology can be substituted by modifying existing production lines. The Atkinson cycle involves a change in valve operations that robs an engine of power but makes it more efficient. In a conventional vehicle (CV), use of this cycle is not acceptable because of the power loss. However, the combination of electric drive with this type of engine in the split hybrid powertrains adopted by Toyota and Ford has proven to be acceptable. While top speed and towing capabilities are sacrificed, acceleration is better than it is for a similar conventional vehicle equipped with an engine of the same displacement. For urban and suburban driving with lightly loaded vehicles, this powertrain provides very efficient and effective performance.

Generally speaking, since both electrical and mechanical power are combined in an HEV, much the same performance as a conventional vehicle can be obtained with a less-powerful and more-efficient internal combustion engine (ICE). As implemented in the best-selling HEVs, reduction in power of the engine is another factor that results in the engine operating more efficiently in the HEV. The greatest commercial successes of HEVs have been accomplished when the engine is "downsized" relative to the most powerful engine available in the same or similar-size models (Table 2-1). Although the Prius is listed as "unique" in Table 2-1 because no conventional gasoline engine is available in a Prius body, it is nevertheless true that, among all vehicles classed by the U.S. Environmental Protection Agency (EPA) as "mid-size," the Prius has the smallest displacement engine (see http://fueleconomy.gov [EPA, 2010]). In all *car-based* HEVs that are the leading sellers, when a comparable conventional drivetrain model is available, the engine in the hybrid is smaller than the largest engine available in the conventional drivetrain. However, in sports utility vehicles (SUVs), aside from the Ford Escape, the engine sizes in terms of cylinder number and total displacement in the conventional and hybrid powertrains are often roughly the same (Table 2-1).

TABLE 2-1 U.S. HEV Sales by Powertrain Technology Group and Vehicle Type, 2000–2008 [Sources: Electric Drive Transportation Association (undated), Hybrid Car Review (2009)][a]

Vehicle Type	Drive types	Smallest engine?	Hybrid type	Model Name	2000	2001	2002	2003	2004	2005	2006	2007	2008	Totals
Car	FWD[b]	Unique	Split	**Prius**	5,562	15,556	20,119	24,627	53,991	107,897	106,971	181,221	158,886	674,830
Car	FWD	Yes	Split	**Camry**							31,341	54,477	46,272	132,090
Car	FWD	Yes	Split	**Altima**								8,388	8,819	17,207
				Totals for class	5,562	15,556	20,119	24,627	53,991	107,897	138,312	244,086	213,977	824,127
				HEV sales by class (%)	59.4	76.7	55.8	51.8	64.1	52.4	54.9	69.5	67.8	62.3
Car	RWD	Yes	Split	**GS 450h**							1,784	1,645	678	4,107
Car	4WD(l)	Unique	Split	**LS 600h**								937	980	1,917
				Totals for class	0	0	0	0	0	0	1,784	2,582	1,658	6,024
				HEV sales by class (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.7	0.5	0.5
Car	FWD	Yes	IMA	**Civic**			13,707	21,771	26,013	25,864	31,253	32,575	31,297	182,480
Car	FWD	No	IMA	**Accord**					653	16,826	5,598	3,405	198	26,680
Car	FWD	Unique	IMA	**Insight**	3,805	4,726	2,216	1,168	583	666	722	3	0	13,889
				Totals for class	3,805	4,726	15,923	22,939	27,249	43,356	37,573	35,983	31,495	223,049
				HEV sales by class (%)	40.6	23.3	44.2	48.2	32.3	21.1	14.9	10.2	10.0	16.9
Car	FWD	Yes	BAS	**Malibu**									3,118	3,118
Car	FWD	Yes	BAS	**Aura**									310	310
				Totals for class	0	0	0	0	0	0	0	0	3,428	3,428
				HEV sales by class (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	0.3

TABLE 2-1 (Cont.)

Vehicle Type	Drive types	Smallest engine?	Hybrid type	Model Name	2000	2001	2002	2003	2004	2005	2006	2007	2008	Totals
SUV	FWD or 4WD	Yes	Split	**Escape/Mariner**					2,993	15,960	22,549	25,108	19,522	86,132
SUV	FWD or 4WD	No	Split	**Highlander**						17,989	31,485	22,052	19,391	90,917
SUV	FWD or 4WD	No	Split	**RX 400h**						20,674	20,161	17,291	15,200	73,326
				Totals for class	0	0	0	0	2,993	54,623	74,195	64,451	54,113	250,375
				HEV sales by class (%)	0.0	0.0	0.0	0.0	3.6	26.5	29.5	18.4	17.1	18.9
SUV	FWD	No	Dual-Mode	**Vue (BAS to ~ 2009)**								3,969	3,399	7,368
SUV	RWD or 4WD(l)	No	Dual-Mode	**Tahoe, Yukon, Escalade**									7,612	7,612
SUV	RWD or 4WD(l)	No	Dual-Mode	**Aspen & Durango**									81	81
				Totals for class	0	0	0	0	0	0	0	3,969	11,092	15,061
				HEV sales by class (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	3.5	1.1
				Car % of Car Truck Sum	100	100	100	100	96	73	71	81	79	80
				Split powertrain share (%)	59	77	56	52	68	79	85	89	85	82
				FWD platform based (%)	100	100	100	100	100	100	99	99	97	99
				Grand Totals	9,367	20,282	36,042	47,566	84,233	205,876	251,864	351,071	315,763	1,322,064

[a] Notes for Table 2-1: data for General Motors hybrids are approximate prior to 2009. Estimates were used from the Electric Drive Transportation Association's Web site for 2007 and from *Hybrid Car Review* for 2008.

[b] Abbreviations in Table 2-1: FWD = front-wheel drive; 4WD = four-wheel drive; ; l = longitudinal mounting of engine, as in rear wheel drive; IMA = Integrated Motor Assist; BAS = belt alternator system

According to the EPA's Fuel Economy Trends report (EPA 2008), the share of hybrids sold in the passenger car category in 2008 was 4%, 2% of SUVs, and 0% of pickup trucks and vans. Within the overall HEV category, the leading seller by far, with 51% of the market in 2008, was the Toyota Prius (Ward and Davis 2009) a design specifically developed to complement the HEV powertrain and enhance overall efficiency (see Table 2-1). *In other words, to date, HEVs designed to maximize fuel efficiency have been relatively more successful than HEVs that compromise fuel efficiency in order to provide more total power.*

From 1997, when the first Toyota Prius HEV was introduced in Japan (2000 in the United States) until now, it has been demonstrated that "learning by doing" can be expected to lead to significant improvements in battery pack and powertrain design over a number of years (Table 2-2). Over three generations of availability in the United States, with each new generation, the Prius's size has been increased, it accelerates more rapidly, and fuel consumption has been reduced (Table 2-2). Similarly, the Ford Escape HEV, which also uses a "split series/parallel" powertrain, has also improved fuel economy significantly from the first- to the second-generation model. The 2010 model of the Lexus RX SUV also improves significantly over the initial 2006 model.

TABLE 2-2 Reduction in New EPA Fuel Consumption per 100-Mile Estimates, for Multi-Generation "Split" HEVs

	Engine Displacement (Liters)	New EPA City Gallons per 100 miles	Percent Reduction	New EPA Highway Gallons per 100 miles	Percent Reduction
2000 Prius	1.5	2.4		2.4	
2004 Prius	1.5	2,1	12.5	2.2	8.3
2010 Prius	1.8	2.0	4.8	2.1	4.5
2006 Lexus RX 400h FWD	3.3	3.6		4.0	
2010 Lexus 450h FWD	3.5	3.1	14	3.6	10
2006 Lexus RX 400h 4WD	3.3	3.7		4.0	
2010 Lexus 450h 4WD	3.5	3.3	11	3.6	10
2006 Ford Escape FWD	2.3	3.3		3.6	
2009 Ford Escape FWD	2.5	2.9	12	3.2	11
2006 Ford Escape 4WD	2.3	3.6		3.8	
2009 Ford Escape 4WD	2.5	3.4	6	3.7	3

2.2 LIGHT-DUTY HYBRIDS THAT PLUG IN, STORE GRID ELECTRICITY, AND THEN USE GRID ELECTRICITY TO MOVE THE VEHICLE: GCHEVs, PHEVs, AND E-REVs

During the 1990s, national advanced and alternatively fueled vehicle design competitions for university teams, sponsored jointly by the Society of Automotive Engineers (SAE), the U.S. Department of Energy (DOE), and U.S. automakers, led to demonstration of the technical feasibility of production of a version of the HEV with a significantly larger battery pack and a charger (Frank 2007). The charger allowed the vehicle to be plugged into a household electrical outlet to draw electric power from the electric grid. The general idea in these vehicles was to provide a battery pack and electric motor with enough power to allow the vehicle to operate all-electrically until the battery pack reached a predetermined state of charge (SOC), then to operate as an HEV. The former circumstance is called charge-depleting (CD) operations mode, while the latter is called charge-sustaining mode (CS). These vehicles were initially called plug-in HEVs (Graham et al., 2001), or grid-connected HEVs (GCHEVs) (Plotkin et al., 2001). One interpretation of these vehicles is that they were compromises that would more cheaply allow at least some zero emissions operation than would pure battery electric vehicles (BEVs). During the 1990s, the priority for developing use of electric operations capability for vehicles was "zero" tailpipe emissions operation, even though some emissions had to occur elsewhere when electricity was generated. A derogative term that has been used is "emissions elsewhere" vehicles.

A concept that has become very important in the evaluation of advanced and alternatively fueled vehicles is "life cycle analysis," or LCA (Elgowainy et al., 2009 & 2010; Gaines et al., 2008; Samaras and Meisterling, 2008; Duvall and Knipping, 2007, Knipping and Duvall, 2007). A subset of LCA is full fuel cycle (FFC) analysis. First for electric vehicles in the 1990s (discussed below), and now for PHEVs, the type of electric generation occurring elsewhere as a result of plugging in must be considered. Because the grid allows for generation from many different technologies and fuels, evaluation of the FFC merits of EVs and PHEVs compared to CVs becomes quite complicated.

In 2001, both the Electric Power Research Institute (EPRI) (Graham et al., 2001), and Argonne National Laboratory (Plotkin et al., 2001) published evaluations of the feasibility of plug-in HEVs, based on projected attributes of NiMH battery packs (see Appendix A for a discussion of battery characteristics). Both studies used the acronym HEV. The EPRI study labeled an HEV that could be operated all-electrically as an HEVXX, where XX was the all-electric operations distance that could be achieved in miles. The estimated all-electric range capability was designed to be available on the Urban Dynamometer Driving Schedule (UDDS), which averages about 20 miles per hour. The EPRI study evaluated the HEV, the HEV20, and the HEV60. Since that time, the phrase "plug-in" used by EPRI has been abbreviated, and today's acronym is the PHEV, with the UDDS range attached, such as PHEV20 and PHEV60. California presently has a test procedure to determine the official all-electric range of the PHEV. The test requires that the vehicle run the UDDS in the all-electric mode.

The Toyota Prius plug-in hybrid appears to have been designed in this fashion (Tanaka, 2009). Its top all-electric speed is 62 mph, which should allow the Prius to operate in all-electric mode during the Federal Test Procedure (FTP) used to determine official fuel economy ratings. This procedure requires tested vehicles to match the UDDS and HWFET driving cycles, with a number of complicated protocols and calculations. Thus, UDDS and HWFET are the driving cycle foundations for corporate average fuel economy tests. Their top speeds are 57 and 60 mph, respectively. The PHEV Prius all-electric range under Japanese test conditions is reported to be 14.6 miles. This range compares to a "modal" distance driven per day of about 9.5 to 19 miles in Japan (or 54% of weekday driving). Toyota's calculations of operating cost savings in Japan indicate that "off-peak" overnight rates are very important for those who will purchase the PHEV to save money. According to Toyota's initial estimates, the savings realized are far greater for the standard Prius compared to a comparable gasoline vehicle (a savings of 147 yen per 19-mile trip) than for the PHEV Prius compared to the standard Prius (a savings of 50 yen per 19-mile trip, using "nighttime" electricity). While Moawad et al. (2009) have recently estimated that the incremental cost of a PHEV relative to an HEV ($1,862 including charger, but not vehicle to plug cord and possible circuit upgrades) can be lower than the incremental costs of an HEV relative to a conventional vehicle ($2,784), the operating savings estimate made by Toyota implies that it will be more difficult to sell the PHEV option to a cost-conscious Prius customer than to make the original sale of the Prius to a conventional vehicle customer. Tanaka (2009) indicates that there is an aim "at a full scale commercialization in 2 years, on the order of several tens of thousands, with widely affordable pricing."

In contrast to the Prius, which will have a 5.2-kWh lithium-ion pack, the prototype Ford Escape plug-in has been said to have a 10-kWh lithium-ion pack (pluginCARS.com, undated). The CD distance "in town" is said to be about 30–35 miles, using "little or no" gas. Ford touted the need for customers to drive enough every day to completely deplete their battery packs. According to Greg Frenette, Ford's manager of battery electric vehicle applications (Berman, 2010):

> If the typical driver is driving up into their driveway at the end of the day, and hasn't depleted the battery and they're driving up with stored energy that they didn't use, they haven't gotten the full value of their investment for the day.

Vyas, Santini, and Johnson (2009), taking this argument into account, examined the pattern of daily driving in the United States and developed a logical argument about the ideal charge-depletion distance to choose for a single PHEV design if the goal were to maximize market potential. Evaluating 10-mile intervals, their finding was that a 30-mile depletion distance would be the best choice. Like the Prius plug-in, the prototype Ford Escape plug-ins use the same approach – make use of the existing electric machinery and control equipment as much as possible and increase the energy storage capacity of the pack significantly more than its power. Nelson et al. (2009) and Moawad et al. (2009) have shown that this approach offers a relatively inexpensive incremental cost for a PHEV.

At the present time, Ford hybrids do not have the ability to attain the peak speeds of the UDDS or HWFET in all-electric mode. The Fusion hybrid is said by Ford to be capable of up to 47 mph, while the current Escape is about 30 mph. The same could have been said about the Toyota hybrids, however, before the Prius plug-in was introduced.

It is important to understand that most urban driving is much more "aggressive" than the UDDS. Acceleration rates and deceleration rates are more rapid. As a result, a PHEV with an official California CD distance rating will in normal driving have the engine come on frequently as the battery pack depletes. Such operation has come to be called "blended" mode operation. This is probably why Ford acknowledged ahead of introduction that some gasoline will be used as its planned future small plug-in hybrid SUV charge depletes.

General Motors is working on a unique PHEV for which it has coined a different name. This is the "Volt," which GM calls an E-REV, for "extended range electric vehicle." This vehicle is being designed to be capable of all-electric CD operation even in aggressive driving. The Volt will likely be capable of 40 miles of all-electric driving if driven on the UDDS under required test conditions, which are at 75 degrees Fahrenheit, with the air conditioner and heater off. However, because "real world" driving is normally more aggressive than the type of driving performed for the UDDS, and also because vehicles operate with air conditioners or heaters on for much of the year, more energy per mile is required to move the vehicle than the UDDS-based test implies. Most Volt owners will realize a shorter CD distance. Thus, GM properly says range is "up to" 40 miles.

2.3 MEDIUM AND HEAVY PLUG-IN HYBRIDS

Comments on the September Workshop version of this document were provided by J.T. Dalum (2009) of DUECO, Inc., and Odyne Systems, LLC. These comments raised the general issue of coverage of plug-in technology for medium- and heavy-duty vehicles, including trucks and buses. Compared to light-duty passenger vehicles about to be deployed, the state of technology for such vehicles is less advanced. Designs generally are in the prototype, early demonstration, or, occasionally, small-volume commercial stages. The comments of Dalum (2009) indicate the significant generic problems for small-volume manufacturers of medium and heavy vehicles.

- Low initial production volume, combined with high start-up costs, contribute to a relatively high acquisition price for current plug-in hybrid systems

- Battery systems for commercial trucks must function well under different conditions and duty cycles than those in light-duty automotive applications. Trucks must often locate the larger battery system on the exterior of the truck, where it is exposed to the elements. Trucks may also operate for much longer duty cycles; commercial vehicles may be driven 12–16 hours per day, or operate for multiple shifts.

- Different system architectures that are designed for high-volume production ─ in which the internal combustion engine can be turned off during driving ─ need to be developed. The development of electrically driven sub-systems such as braking; power steering; heating, ventilation, and air conditioning (HVAC); and other systems need to be brought to high-volume production for medium- and heavy-duty trucks.

Because of their high-volume production and sales, passenger vehicle manufacturers such as Toyota, Ford, and General Motors have the ability to conquer all three of these difficulties — and have done so for HEVs. The second bullet identifies a particular problem for the medium-duty and heavy-duty manufacturers. Without electrical components to perform the work needed and provided by an engine and alternator at idle, the engine in many circumstances has to be left on. This operating condition diminishes fuel savings in the current generation of vehicles. Although urban delivery vehicles do often operate far more hours per day than do passenger vehicles, the annual miles driven for diesel single-unit trucks (urban delivery trucks) average from 15,000 to 20,000 miles per year, depending on size (Bertram et al., 2009). This range of miles compares to about 12,500 miles per year for light-duty passenger vehicles. Apparently, the average speed of operation of urban delivery trucks is considerably lower than that of passenger vehicles. This relationship is also true for transit buses (Goldman, 2009) and school buses (M.J. Bradley & Associates LLC, 2009). Many stops per mile are involved in operation, with far more idling per mile than for passenger vehicles.

Heavy-duty "combination" trucks, which carry most freight between cities, do not idle on the roadway, but most today have "sleeper" cabs and idle overnight when parked to provide cab comfort as the truck driver (or drivers) sleep. Plug-in technologies are being developed for installation at truck stops to serve this market (EPRI, 2009; Gaines et al., 2006; Gaines, 2008).

When it comes to the provision of peak electric motive power to provide acceleration and continuous power to allow for electric cruising, medium and heavy trucks are very challenging because they adopt ***very*** significant engine downsizing compared to passenger vehicles. This means that the engines are actually small relative to the mass carried by the vehicle. The power of engines in the heaviest commercial trucks is well below the power that a battery and motor would require to capture available braking energy. Thus, to match the proportion of regenerative braking that is possible in light-duty passenger vehicles, the motors would have to have much larger kW ratings than the engines currently have (Santini et al., 2005). M.J. Bradley & Associates LLC (2009) estimated that the amount of regenerative braking energy recovered in a tested plug-in hybrid school bus (with a motor of considerably lower kW rating than the engine) was not enough to offset the added fuel use needed to move the added weight due to the battery. Battery volume and mass can also have detrimental effects on both fuel consumption and load-carrying capacity for fully loaded trucks, which often have a legally limited maximum weight. General Motors' automotive experts do not anticipate plug-in electrification of large inter-city combination trucks (Satyapal and Aceves, 2009).

Another reality is that most commercial trucks use diesel engines. Both the diesel and electric drive via hybridization are expensive. Doing both involves some overlap of benefits. Diesel engines have a lower fuel flow rate at idle than do gasoline engines, so there is less idle savings to be had when hybridizing a diesel engine. In contrast to the 30-40% estimated savings for hybrid passenger vehicles noted in Appendix B, the urban driving savings estimate by Dalum (2009) for the Odyne/DUECO medium-duty plug-in conversion of electric utility "trouble trucks" (see definition in section 1) was 15%. In testing diesel hybrid school buses, M.J. Bradley & Associates LLC (2009) found essentially no benefit for the prototype straight hybrid. While the plug-in hybrid school bus sharply reduced fuel consumption during CD operation, fuel consumption rose during CS operation as a result of battery mass, even though lithium-ion battery packs were used. Considering upstream emissions, almost no net benefits were estimated for the plug-in hybrid school bus. Both the trouble truck and school buses used a one-electric machine parallel and a rear wheel drive (RWD) system with no engine downsizing. For urban buses using a much more complex two-electric machine hybrid powertrain, a well-designed comparative analysis by Walcowitz (2006) indicated dynamometer test cycle savings of 43% at 7 mph "Manhattan" conditions, which dropped to 20% at 23 mph with air conditioning on. Field tests of diesel hybrid versus conventional diesel buses for Manhattan conditions, at about 6 mph where air conditioning was included (and was clearly very important), had fuel consumption reductions varying from 22–28% (Barnitt, 2008). For field tests in Seattle at speeds about twice as high, the reduction was 20% (Walcowitz, 2006). Lead-acid batteries were used in the New York City hybrid buses, while NiMH batteries were used in the Seattle hybrid buses.

Gasoline hybrid buses have recently been introduced (HybridCenter.org, undated). Diesels have typically been the power plant of choice for urban buses because of reduced idle fuel flow, extra low rpm torque, and durability. Substituting electric motors and batteries boosts low-speed torque, taking this advantage away from the diesel. Both can eliminate fuel flow at idle – using only the motors and batteries means that reduced fuel flow at idle does not have to be paid for twice. Motors and batteries in hybrids eliminate many hours of engine operation, making the added durability of the diesel less important. The initial gasoline hybrid buses offered by ISE Corporation are reported to be certified to lower emission standards for NO_x and particulate matter than their hybrid diesel and even natural gas counterparts (HybridCenter.org, undated). The joint effort by the EPRI, Ford, and Eaton to develop a Ford F550 (class 5) medium-duty electric utility "trouble truck" includes efforts to match the hybrid equipment to both gasoline and diesel engines (Green Car Congress, 2007).

Odyne/DUECO's comments on their trouble truck plug-in hybrid presented two examples that estimated that fuel reduction in daily operation could be from 40% to 65%. The large daily operations reductions resulted primarily from elimination of both the hours of engine operation supporting power take-off and simply from idling. The estimated fuel-savings percentage per day therefore rose with the amount of eliminated idling time and power take-off operation. Twenty of these trucks have been produced since 2007. In addition to the relatively large utility trouble trucks served by the Odyne/DUECO system, the EPRI (2008) has been working with Ford and Eaton to develop a large pickup truck-based plug-in hybrid trouble truck. The design requirements for this trouble truck include the following:

> 30 kW of standby AC generation capacity with 5 kW of export power and standby operation time of at least six hours, running the bucket, power tools, lights, and accessories without the need to run the engine (Green Car Congress, 2007).

While these vehicles may be highly valuable to the electric utility industry, this application is relatively limited from a national perspective.

Dalum (2009) indicates where one should look to find a broader market for the Odyne/DUECO type of system:

> For example, trucks that use cranes, compressors, welding equipment, or are used in applications such as gas utility maintenance, refrigeration, rescue, refuse and construction may benefit from plug-in hybrid technology.

It seems to this author that the first priority is to understand the commercial truck market's in-use operating behavior better by estimating the total size of the idle reduction and power take-off market before deciding on deployment support. Gaines et al. (2006) made a rough initial attempt concerning idling. However, the data is not particularly good. As Dalum (2009) notes:

> In order to optimize plug-in hybrid designs, research data needs to be collected from real-world working fleets, in terms of actual fleet utilization, miles driven, time at idle, power requirements, fuel consumption, and other operational factors.

The present Odyne/DUECO system uses lead-acid batteries. Dalum (2009) also noted that battery technology improvement is critical:

> Plug-in hybrid systems typically require much larger battery systems. The additional weight can create a problem for certain applications. As lightweight, more advanced batteries enter the market and become affordable, the number of applications where plug-in hybrid technology can be used will increase.

The high cost of lightweight batteries was mentioned as a deterrent. The present Odyne/DUECO system uses a 35-kWh pack. The Nissan Leaf electric passenger car (Section 2.4.2) will have a 24-kWh pack. A factory is envisioned that can produce hundreds of thousands of these units. Perhaps coming lightweight and compact lithium-ion battery cells for automobiles will allow development of a smaller, lighter battery pack that is reliable and inexpensive enough to serve Odyne/DUECO's needs and will create the potential for the wider market identified by Dalum (2009). Another possible spin-off that could benefit medium- and heavy-duty plug-in hybrids could occur if all-electric buses succeed (Section 2.4.3). These vehicles obviously would require electric auxiliary equipment of a size appropriate for the medium and heavy plug-in hybrids requiring cab comfort at times when the vehicle is stopped.

Another plug-in commercial vehicle with a parallel RWD plug-in hybrid powertrain that has been in development is the former DaimlerChrysler Dodge Sprinter van (Worldcarfans.com, 2006; Portmann, 2008), which was tested by the *New York Times* (Abuelsamid, 2007). Although 10 test vehicles were put into service in the United States, this vehicle program did not continue in the United States following the split-up of Daimler and Chrysler. Apparently, however, it continues in Europe, where it is highlighted on the cover of the latest Daimler AG 2009 Sustainability Report, *Daimler 360° Facts* (Daimler AG, 2009a). In an extended Web-only version of the report, Daimler AG, (2009b), states:

> "…The van can cover up to 30 kilometers all electrically, on a single battery charge, on a highly demanding inner-city route in Paris, fuel consumption was reduced by 40 percent to just 10.1 liters per 100 kilometers, as compared to pure diesel operation. Sixty-two percent of the route was covered by purely electric means."

These figures can also be found in Portmann (2008), along with the fact that the average speed of the tests was 5.4 mph. The amount of miles driven all electrically was reported as 12.6 miles. Over the full 20-mile course, 8.7 kWh was used (about 58% of the ~ 15-kWh nameplate battery capacity).

For New York tests of the plug-in hybrid Sprinter, the average speed was much higher at 15 mph. All-electric operation occurred for an average of 6.9 miles, using about 6.7 kWh. Only about one-third of the 22-mile route was driven electrically. Within the cores of these two major cities, the percentage reduction in fuel consumption was 40% in Paris and dropped to 36% in New York. The pack size was limited by available volume. Even though Daimler AG estimates that the cost of the NiMH battery is the same or possibly lower than that of the lithium–ion battery (DaimlerAG, 2009b), over the multiyear program, the battery chemistry was switched from initial use of NiMH to lithium ion in order to fit more kWh into the vehicle. Even so, on one charge, the percentage of miles that could be electrified in daily driving by this vehicle was well under 50%, even in very slow, stop-and-go driving with a high fraction of idling. This result illustrates the problem of finding enough space so that a pack can match the daily driving needs of commercial delivery trucks charged only overnight.

Another way of looking at the challenge for commercial trucking is to think of the proportion of daily hours of operation supported by an overnight charge. In the case of the Paris application for the Sprinter, the Paris drive cycle, at 20.3 miles and 5.4 mph, can be completed in 3.7 hours (Portmann, 2008). If the driver is out of the vehicle and the keys are off for a number of hours per day, then this might support a day of work. If not, then having the ability to perform more than one charge per day would be desirable, and fast (Level 3) ─ but expensive ─ chargers would probably be necessary. Both the cost of the charger and the cost of time for lost labor for the driver must be considered. In the New York case, the need for support from fast chargers is even more clear because in that cycle case, one drive cycle (operating route) is run in 1.5 hours. In higher-speed suburban routes, charge-depletion might occur even more rapidly. The medium-duty electric utility trouble truck, because it is bigger than the Sprinter Van, is large enough to accommodate a battery pack with a nameplate capacity 35 kWh, which is more than twice the capacity of the Sprinter. This pack must be large to support several hours of operation. Dalum's (2009) examples of operation included a total of 4 and 6 hours of time during which it was presumed that the vehicle was stopped and the engine would have otherwise been operating, either at idle or when running power-take-off equipment.

The Sprinter Van plug-in hybrid development effort puts into perspective the time from research and development to deployment. The primary interest of Clean Cities is support of deployment efforts. This report was written in support of development of a five-year plan from 2010 to 2015. The joint effort by EPRI, with support from several sponsors, to work with DaimlerChrysler to develop a plug-in hybrid version of the Sprinter began in 2004, starting with testing of four vehicles in various locations in the United States (Penton Business Media EC&M, 2004). Five years later, it is not yet clear whether Daimler Sprinter plug-in hybrids will be available in the United States for deployment in hundreds or thousands of vehicles.

Comments received on the September workshop version of this report from Fraser Murison Smith of ElectraDrive suggested that Clean Cities should support efforts by ElectraDrive to develop plug-in hybrid retrofits of pickup trucks. A recent Web posting indicates that ElectraDrive is in the early phases of a plug-in powertrain development for pickup trucks. One pilot conversion of a Dodge Dakota pickup to extended-range electric drive will enter road-testing around the middle of 2010 (Marketwire, 2009). This project conducted with the County of Alameda is supported by the Greenlight Initiative of the California State Automobile Association. Other efforts to develop plug-in hybrid conversions of either new or used SUVs and/or pickup trucks could be cited here. Some of these efforts may succeed, and/or major automakers may choose to produce such vehicles themselves. It is possible that significant success could emerge in the next five years. However, at this time, no announcements are evident of major commitments to mass-produce either retrofits or original equipment manufacturer (OEM) versions of plug-in powertrains for RWD light-duty vehicles (i.e., pickups and large SUVs) subject to dynamometer emissions testing. In light of the long development time line for the Dodge Sprinter plug-in hybrid, and the uncertainty of success at the stage where only a few vehicles are being tested, it does not seem prudent to suggest at this time that Clean Cities should prepare to support deployment of such powertrains.

2.4 ELECTRIC VEHICLES (EVs)

2.4.1 EVs in the 1990s

In 1990, General Motors announced its intention to produce electric vehicles. California, taking this announcement into consideration, later created regulations specifying a share of electric vehicles to be sold in California – ultimately 10%. Several manufacturers produced and field-tested several EVs, predominantly using NiMH. Nissan produced an EV using the lithium-ion battery chemistry. GM produced a two-seat sports car model ─ the EV1 ─ with a lightweight, aerodynamic body and using either lead-acid or NiMH batteries. Toyota produced a small four-to-five passenger SUV in the RAV4 body. Honda produced a specially designed compact four-passenger vehicle. Nissan produced a five-passenger station wagon.

As of 1997, Chattanooga had put 16 electric buses into service, either 22- or 31-feet in length. Lead-acid batteries were used. The smaller buses used a battery switch-out approach, with battery changes taking 10–15 minutes. The packs in the larger buses were too heavy and costly to switch out. They took 6–8 hours to charge. At the time, fast charging, at 2 hours, was planned. The range of the buses was about 40–50 miles, with a top speed of 40 mph (DOE, 1997).

2.4.2 Present-Day EV Types and Prices — Light Duty

As a result of the sharp rise in oil prices this decade relative to the 1990s, and considerable technological progress in lithium-ion (Li-ion) battery chemistries, a new wave of enthusiasm for electric vehicles (EVs) has emerged. Some European cities, such as London and Oslo, have adopted strong incentives in support of EV use within the city proper. Combined with 2008's higher oil prices and increasing concern for global warming, major automakers have made commitments to produce "city EVs" for use in congested low-speed driving. Santini and Vyas (2009) for the United States and Golob and Brownstone (2005) for California have shown that the proportion of cars in the vehicle population increases as population density increases. Thus (and not surprisingly), EVs that are under development are "City" cars or "City EVs." They are generally small, even among cars. BMW has been testing an EV version of its Mini, which becomes a two-seater when the battery is included. DaimlerChrysler is developing an electric version of the "ForTwo," a small two-seater now available in the United States. Commercial introduction will start in Europe, although limited numbers should be made available in the United States for evaluation purposes.

Mitsubishi has developed the i-MiEV, a "Lilliputian four passenger EV with a 16-kWh battery pack that may be priced at upwards of $45,000" (Squatriglia, 2009). Mitsubishi plans more models and will have a cooperative agreement with Peugeot of France to produce EVs for Peugeot. At the Green Car Congress in June of 2009, Menahem Anderman predicted that sales of EVs and E-REVs with 15–16 kWh of capacity will lead the worldwide market sales of vehicles equipped with lithium-ion batteries by 2011, with a total of 8,000 vehicles, half of which would be i-MiEVs. The i-MiEV, like the Mini-E and ForTwo EVs, is also planned for initial commercial introduction in its location of manufacture (Japan), with plans for broad commercial introduction in the U.S. market a few years later. However, limited numbers are being evaluated in the United States.

Announcements concerning EVs and battery packs have been relatively frequent in recent months. Nissan has announced the development of three different EVs that use Li-ion packs. The largest of these — the Nissan Leaf — is said to be based on the Nissan Versa platform, a five-passenger vehicle rated as a midsize vehicle by the EPA. In terms of interior volume, the Versa is a bit smaller than a Prius. The Leaf will also be introduced overseas (in Japan), in competition with the four-passenger Mitsubishi i-MiEV, before its introduction in the United States. It is to be built initially in Japan at a volume of 50,000 vehicles per year. If successful, the next production location is to be Smyrna, Tennessee (Ventner, 2009). Battery packs may be produced in Japan, the United States, the U.K, France, and Portugal. The battery pack is to be leased rather than purchased, consistent with the Better Place business plan (see Section 2.4.4, EV Charging Systems, Plugs, and Household Infrastructure). Charging at 200 V (no amperage specified) at home (presumably in Japan) is said to take about 8 hours (Ventner, 2009). As noted elsewhere, the time it takes to charge an EV depends on both volts and amps.

Both the Leaf and the i-MiEV are to have a rated CD distance of 100 miles. Passier et al. (2007) simulated a "Prius-like" set of plug-in hybrids, including split, parallel, and series types. The series type was similar to an E-REV and was estimated to operate all-electrically in all conditions aside from on European Motorways. Based on the results, if an EV were rated on the basis of the UDDS, in real-world European driving in cities and two-lane country roads, the actual CD would be from 8% to 32% lower than the rated CD. This simulation ignored the effects of cold battery warm up, cold temperatures with snow-covered roads, or air conditioning. Actual CD could drop by considerably higher percentages in extreme weather conditions. City EVs may be more likely to experience temperature extremes, as it could be argued that they will be more likely to be parked outdoors rather than in garages as in the suburbs. However, if City EVs were owned by relatively high-income city residents and therefore parked and charged in garages, the effects of extreme temperatures could be mitigated. Although charger costs could be considerably higher in cities, it is also true that parking space costs and fuel costs also tend to be considerably higher in such locations; thus, the incremental cost may not appear to be as high to those with the ability to own such a vehicle in such locations.

Tesla Motors (2009a), which has developed the extremely high performance two-seat electric Tesla Roadster, plans to produce a sedan, the Model S, seating five adults and two small children. As of September 2009, Tesla had sold 700 roadsters, which use Li-ion batteries, at prices above $100,000. Tesla's technical description did not specify the kWh capacity of the battery or its chemistry.

Tesla received approval for about $465 million in low-interest loans from the U.S. Department of Energy to accelerate the production of the Model S, a "family sedan that travels up to 300 miles per charge." Tesla will use $365 million for production engineering and assembly of the Model S. Tesla will use $100 million to build manufacturing capabilities to produce batteries and drivetrain components in California. The loans are part of the Advanced Technology Vehicles Manufacturing Program (ATVMP), which provides incentives to new and established automakers to build more fuel-efficient vehicles. The loans are unrelated to the stimulus package or "bailout" funds that GM and Chrysler received. The Model S has an anticipated base price of $49,900 after a $7,500 U.S. federal tax credit. Tesla expects to start Model S production in 2012.

Tesla has never applied for federal funds for the Roadster, an American sports car that consumes no gasoline whatsoever. Tesla expected the Roadster business unit to be profitable by 2010. Tesla, which is privately held, will finance sales and marketing for the Model S through private capital.

Still another very informative data point is Tesla's stated cost of $12,000 for a replacement battery for the roadster (Tesla Motors, 2009b). For the Model S, the time required for a battery swap is listed as 5 minutes. In the Frequently Asked Questions (FAQ) menu, it is stated that normal battery life for the Model S can be expected to be 5–7 years but with proper management could be as high as 10 years. According to Cars.com (undated), the standard vehicle warranty for Tesla's 2009 Roadster is three years, with a $5,000 option for five years. Regarding interior volume issues (discussed elsewhere for PHEVs), the Model S brochure indicates that there is actually a trunk under the hood. Although the vehicle looks like a four-door, five-passenger sedan, it is claimed that there is seating suitable for two children in the back, for a total of seven occupants.

Under Roadster Battery Pack Specs on the "theirEarth" web site (2008), the energy storage rating of the roadster's pack is 53 kWh, and the motor power is 185 kW, requiring the pack to be in the 190–200-kW range. The California Air Resources Board (2008) quoted 52 kWh. At the stated roadster battery pack replacement price of $12,000, the estimated *consumer's* cost per nominal kWh works out to be a very low $240. The computation of a $240/kWh cost is a result consistent with the *manufacturing cost* estimates of the potential costs of lithium-ion batteries at similar W/Wh ratios made by Kromer and Heywood in 2007 and, more recently, by Nelson et al. (2009). For Nelson et al., necessary annual pack production volumes were included in the cost model. For the nickel-cobalt-aluminum cathode and graphite anode (NCA-G) chemistry, a cost of $240/kWh to the manufacturer (not the retail price) would require that more than 30,000 packs per year be produced. Tesla has not reached that level, having sold only several hundred Roadsters to date. However, they may be working from a forward projection of pack production costs five years after introduction, when the first round of replacements become necessary and pack production volume is anticipated to be in the tens of thousands. Another possible consideration is that Tesla is anticipating technological improvements that would allow an increase in the useable fraction of the future replacement pack because fewer total nominal kWh will be required to serve the same function. Yet another is that a replacement pack might be smaller in kWh capacity than the original pack — see section 2.4.4.

The Tesla roadster driving range was reported in its FAQ as estimated to be 224 miles on the combined city/highway EPA driving cycle. If this rating literally means the certification cycle and does not refer to EPA's new window-sticker value, then customers may be in for a disappointment when they drive the vehicle on the open road like a sports car. Passier et al. (2007) estimated that the electricity consumption of a series plug-in electric hybrid during charge depletion would be roughly double in European Motorway driving — the kind of driving that sports car owners may desire — as it would be when compared to the UDDS and Highway (HWY) cycles (the latter two were almost identical and are the basis of the EPA city and highway tests). This estimate would bring the range down to 122 miles, or less than two hours of driving at European Motorway speeds. However, if driven at legal speed limits on U.S. interstates, the range demerits would be considerably reduced: Tesla's FAQs gave a range of 170 miles in spirited driving.

2.4.3 Present-Day EV Types and Prices — An Urban Transit Bus

A few units of the new Proterra lightweight composite body, all-electric bus with lithium-ion batteries (titanate chemistry) are to go into service in California. Foothill Transit will be conducting initial tests of three 38-passenger Proterra buses and two fast-charge stations designed to charge the vehicle in 10 minutes (Goldman, 2009). The total cost for these initial buses and charging stations is approximately $5.6 million, or about $1.9 million per bus (Goldman, 2009; Foothill Transit, 2009). By comparison, 40-foot hybrid buses recently cost about $450,000–550,000, compared to about $300,000 for a conventional bus (Environmental and Energy Study Institute, undated).

For the initial three-bus, two-year tests by Foothill Transit, average operating speeds will be 12.5 mph, and the buses will be in service 10–13 hours per day. Proterra presents cell test results indicating about a 10% deterioration in "capacity" (not identified as kW or kWh) over a span of 7,000 charge-discharge cycles (Goldman, 2009). Production facilities are under construction to allow a maximum output of 500 buses per year. Proterra does not report electricity consumption in kWh at this time. However, they report "diesel energy equivalent consumption per gallon," from tests conducted at Pennsylvania State University's Altoona facility. For the Central Business District (CBD) cycle, which averages 12.6 mph, the reported results are 21.3 mpgge. This result may be compared to values of 2.3 mpg for diesel buses in New York City operating at 6 mph, and 3.2 mpg for hybrids. The Proterra tests were performed at a gross vehicle weight of 36,680 lbs, which simulated a full complement of 38 seated passengers, another 34 standing passengers, and a driver (Yoney, 2009). Although air conditioning may not have been in use, the New York City tests undoubtedly did not have a full passenger load at all times.

According to Goldman (2009), Proterra does not provide the kWh rating of the pack, but it did provide a chart of kW requirements for operations and fast charging. The plot implies a peak battery pack power of more than 160 kW and continuous power that is a bit above 120 kW. Yoney (2009) cites the motor peak capacity at 150 kW and the continuous rating at 100 kW, ratings that are generally consistent with these battery pack estimates. A 10-minute charge at 120 kW would lead to a charge of about 20 kWh, a surprisingly low result. If the pack's useable energy for fast charge was 70% of nameplate, the nameplate capacity would be 29 kWh (by another approach using other educated guesses, the total would be 34 kWh and useable capacity about 24 kWh). The test simulation plot in the Proterra presentation, combining three CBD cycles, two ART (arterial) cycles, and one COM (commuter) cycle, implies that depletion (at an average speed of 19.2 mph) may occur within less than one hour. Charging includes a block at full capacity, a delay, and then a variable tapered charge ─ apparently to fill the pack completely. Yoney (2009) indicated that a charge takes 20 minutes. These estimates may simply be an artifact of the test, but if this speculation is correct, the numbers imply that the fast-charging capability and surprisingly high cycle life of the lithium-titanate chemistry are necessary to make this electric bus technology work in this application. Even with fast charging, it appears that a fair amount of "down time" for charging is necessary.

Considering the earlier computations related to the Daimler AG plug-in hybrid Sprinter tests and these computations related to the Proterra bus, it seems clear that most commercial and transit vehicle operations, where several hours of operation a day are required, will also require fast (Level 3) charging in order to be feasible.

A possibly interesting observation is that the fuel economy tests for the Proterra bus show a "U" shape relative to average speed for electricity consumed per mile. The average speeds of the cycles are as follows: CBD – 12.6 mph, ART – 24.8 mph, and COM – 43.8 mph. Diesel-equivalent fuel economy estimates by mph were: 12.6 mph – 21.35 mpgge; 24.8 mph – 17.55 mpgge; 43.8 mph – 29.23 mpgge (Yoney, 2009, Goldman, 2009). Extrapolated to light–duty, all-electric operation of the Volt, these results suggest that everyday driving in suburban residential areas may be the most efficient mode for all-electric drive operation.

2.4.4 EV Charging Systems, Plugs, and Household Infrastructure

The concept of designing EVs to have switchable batteries in order to create a "standard" refueling model for EVs (i.e., refueling at stations away from the dwelling unit, much the same as occurs at gasoline stations) has been promoted heavily by Better Place (2009). The company plans to be an infrastructure provider, with battery costs folded into the cost-per-mile service charge for operation of an EV. The EV owner will purchase the vehicle but lease the battery. Better Place will apparently own the recharging infrastructure and develop methods for automatically charging EV owners. Charging stations will be placed at or near dwellings, work, and elsewhere. For long trips, where owners would not have time to wait for the vehicle to charge, there would be battery-swapping stations. The Better Place Web site indicates that a battery-swapping station capable of executing a swap in 60 seconds exists in Japan. Renault-Nissan is working with BetterPlace. In the United States, Better Place indicates that it has formal working relationships with governments in Hawaii and California.

An interesting feature of the Tesla Model S is that battery pack choices will offer a range of 160, 230, or 300 miles per charge. In the context of Better Place's plans, Tesla's options raise the question of standardizing the design of switchable batteries. Based on the Better Place Web site's video of the pack-switching system in Japan, the system is designed for one vehicle type with specific battery dimensions. If multiple-pack configurations developed for different customers must be offered, issues concerning the complexity in design and the operation of such battery-switching stations will need to be addressed.

Tesla says that the Model S, which carries its charger on-board, "can be recharged from any conventional outlet." However, the time it takes to charge the vehicle from a conventional outlet could be a deterrent. An educated guess is that the vehicle will use 0.3 kWh per mile. At 160 miles, 48 kWh of charge would be needed. With a 1.4-kW charger compatible with a standard 120V, 15-amp conventional outlet, it would take more 32 hours to fully charge the vehicle. This is not to say that some owners could not cleverly manage a charging strategy. For example, a daily driving schedule amounting to 40 miles or less would require about 12 kWh or less of battery power per day, which would require about 9 hours or less of overnight charging time. If the vehicle had previously built up a charge to maximum allowable SOC, a reasonably consistent 40-mile daily driving schedule would be workable with overnight "topping off." If long trips that required 160 or more miles of range were followed by several days of low use of the vehicle (with a plug available), charge could be built up again. If a plug with higher capability were available, recharging the vehicle more quickly would be even more workable. It is anticipated that standard on-board vehicle chargers will be compatible with both standard and 220–240V, 30-amp circuits, where the charger can operate at several kW, sharply reducing charging time (Duvall et al., 2002).

Most likely, owners of EVs will want higher charging rates than are available from standard conventional plugs and will find it necessary to pay the extra infrastructure costs for high-rate charging – on the order of $1,000 at a minimum for an existing garage or carport, if the parking location is next to an existing, readily upgradeable circuit and high-rate charging capability is already incorporated into the vehicle. If the parking location is not as favorably located and/or the high-rate charging capability is not already built in, considerably higher costs would likely result. PHEV purchasers may be more reluctant than EV purchasers to invest in high rate-charging capability, having fewer anticipated kWh over which to amortize the costs. It would certainly be a plus if Better Place were to offer a charger installation service with costs amortized into battery pack leases and/or kWh charges. Higher charging rates would likely lead in particular to greater use of EVs and also of PHEVs and E-REVs, which would lead to a faster financial return to Better Place. Package arrangement for many Level 2 or 3 (high-rate) chargers in an individual parking lot could reduce the cost per charging station, but the challenge of matching the construction of such concentrated plug outlets to similar concentrations of EVs would be daunting, particularly for areas serving individual households.

Costs of charging infrastructure consist of several distinct elements — we discuss three here: (1) the charger, which will be on the vehicle for Level 1 (120V systems with varying amperages) and Level 2 (240V systems with varying amperages) charging; (2) the electric vehicle supply equipment (EVSE) connecting the vehicle to the charging station plug — the cord/connector; and (3) the charging circuit and, if any, metering equipment. The most costly of these by far is the third, the charging circuit and its metering equipment.

Moawad et al. (2009) estimated a consumer retail price of a *charger* that is on board a vehicle and capable of both Level 1 and Level 2 charging (assume 3.3 kW) at $800. This estimate assumed a relatively high volume of sales — in the tens of thousands. In addition, for an on-vehicle charger, the Electrification Coalition (2009) estimates lesser costs of around $400 per charger, declining over time. These chargers will probably carry a rating of at least 3.3 kW and perhaps of 6.6 kW. For higher kW ratings that remain under the Level 2 on-board charging umbrella, costs will probably be higher.

The charging rate (kW) issue is apparent in the technical specifications of the EVSE cord/connector equipment for the Tesla Roadster. Individuals capable of paying $100,000 and more for an electric sports car may not wish to have to manage the charging of their EV carefully. Tesla lists the price of optional charging connectors at $600 for a standard conventional 120V/15-amp capable connector. Morrow, Karner, and Francfort (2008) estimate costs for a 120V /20-amp connector at $250, if produced in volumes of 100,000. For the much more capable 240V/30-amp connector, Tesla's 2009 list price is $1,500. For a future 240V/40-amp capable connector produced at a volume of 100,000 units, Morrow, Karner, and Francfort (2008) estimate a cost of $200. However, for Tesla Roadster's high-income customers who place a high value on their time, even the rate of charging supported by a 240V/30-amp circuit (Level 2) may not be acceptable. A "high power" cord/connector is listed for $3,000. Standards for communications with the grid and vehicle will require built-in electronic controls and therefore the relatively expensive cord/connectors, as the pricing list for Tesla EVs indicates.

Although there are technical options for on-board Level 3 (i.e., 480V systems with varying amperages) charging, the costs of thermal management of such fast charging will probably cause Level 3 chargers to be located off of (not on-board) the vehicle. Level 3 charging stations discussed below include a charger. Otherwise an on-board charger is assumed. The time challenge involved in the fast-charging requirements of an EV clarifies the merits of the 5–10-minute battery-swapping idea of Better Place. Tokyo Electric Power Company (TEPCO) has been assessing and publicly discussing the value proposition for fast charging (Anegawa, 2009). The cost of a 50-kW fast charger is illustrated at $35,000; a 200-kW charger's cost is listed at $150,000. It is not clear whether these figures are intended to represent installed costs, including land costs and trenching for cables, or just the cost of purchase of the charging station itself. The Electric Transportation Engineering Corporation (2009) estimated the installed cost of a Level 3 public charging station with two 30-kW plugs to be $64,000 Canadian dollars. Level 2 charging *stations* (i.e., located off-board of vehicles) are in the market today for $2,000–$3,000, according to the Electrification Coalition (2009). Note that the TEPCO numbers imply that the cost per kW of capacity rises with increasing kW of capability. For the 3.3-kW case, the cost is $242/kW. For the 50-kW case, the cost is $700/kW, and for the 200-kW case, the cost estimate is $750/kW. The Electric Transportation Engineering Corporation (2009) estimated the installed cost of a Level 2, two-plug public charging station to be $12,900 Canadian dollars. For a residential installation, costs for one plug were estimated to be $2,300 Canadian dollars. For a 10-plug, commercial Level 2 facility, costs were estimated at $31,400 (Canadian), which is more expensive per plug than estimated for the residential Level 2 charger.

TEPCO approaches the infrastructure cost question from a systems-level perspective to support the use of electric vehicles that would be suitable for its employees and business fleets. Its argument is that the cost of fast charging makes it desirable to use a minimum number of fast chargers. TEPCO did find system-level benefits for its existing fleet by installing two well-located 50-kW chargers. Although the chargers were not used often, their existence gave the EV drivers confidence to drive consistently further from home base (Level 2 chargers), allowing much better utilization of the fleet, with many more miles electrified.

The target times of charging with the 50-kW charger were stated to be approximately 5 minutes for 25 miles of range and 10 minutes for 37.5 miles of range when the small commuter electric vehicles being sold in Japan are charged. It was stated that the 50-kW chargers are for "normal passenger vehicles, not super EVs, trucks and buses." It was noted that the "large charger" was not economical and not easy to install. Presumably, the Tesla Roadster and Model S would fall in the category of "super EVs." Consequently, this raises the question of whether multiple quick-charge infrastructures would be necessary for "normal" EVs and "super" EVs. If only 50-kW infrastructure was installed in support of "normal" EVs, then Tesla roadsters with ranges from 160 to 300 miles could take from 45 to 80 minutes to charge, ignoring the fact that completing the last few kWh of charge should not be carried out as rapidly if long battery life is to be assured. For normal EVs with 100 miles of range, the time required for charging would be about half an hour. If the normal EVs traveled on interstates at about 67 mph and could always stop at an unoccupied charging station at just the moment charge was depleted, about 25% of trip time would be involved in charging. This estimate ignores the realities of variability in charger location relative to route(s) taken. These are approximations. They illustrate the magnitude of the inter-city charging problem from the point of view of the EV driver.

From the point of view of the owner of the infrastructure, the problem is that a quick charger may not pay for itself. Only at the systems level were the fast chargers seen as worthwhile by TEPCO. Franchises for electric-charging stations that are depending on revenues exceeding costs would be unlikely to have a "business case." A recent presentation by Delta Energy and Environment illustrates the problem. Quoting the Environmental Defense Fund (EDF), the presentation gives an example of a charger costing 10,000 euros which returned

45 euros per year. Another example from Scottish Power indicated that recovery of charging infrastructure costs would require that a cost of 45 euro cents per kWh would have to be charged (Harkin, 2009). If EV owners paid such prices on a regular basis, their energy costs per mile in the United States would exceed those for comparable conventional vehicles. However, it must be remembered that the TEPCO analysis shows that a business case may exist at the systems level because a well-designed, fast-charging infrastructure with minimized costs could greatly increase the marketability of EVs and the rate of utilization of the battery packs. However, the challenge involved in finding a cost-effective solution is clearly very great.

Nissan's plans for electric vehicles are ambitious. Introduction of the Leaf to the U.S. market will take place in late 2010. The cost is projected be about $30,000–$35,000. For a time (i.e., for up to 200,000 vehicles, if sold by the end of 2014), the vehicle will be eligible for a $7,500 tax credit, which could, at an approximately $30,000 price before credits, make it comparable in initial outlay to a Prius or Volkswagen Jetta diesel. The battery is to be 24 kWh in capacity, with 90 kW of power. The W/Wh ratio of 3.5 is very close to the ratio of the Tesla Roadster ─ essentially the same considering uncertainty. If we assign a long-term, high-volume manufacturing cost value as low as $240/kWh, the battery pack cost would be $5,760, which is well under the initial U.S. subsidy value of $7,500 for packs of 16 kWh or more. Looked at another way, for 24-kWh packs (e.g., Nissan Leaf), the U.S. government provides a subsidy of $312 per kWh; for 16-kWh packs (e.g., Chevrolet Volt), a subsidy of $469 per kWh. If packs can be manufactured for per-kWh costs that are lower than these subsidies, manufacturers have a significant incentive.

According to Muller (2009):

> By 2012 Nissan will have a lithium-ion battery plant and a retooled electric-vehicle assembly line in place in Tennessee, funded in part by a $1.6 billion loan from the U.S. Energy Department. Nissan plans to build 150,000 EVs and 200,000 batteries a year in the U.S. and announced similar plans for battery factories in Great Britain and Portugal.

Though very likely for a different chemistry than Nissan and NEC Corporation (a battery manufacturer) will use, at volumes of 200,000 packs per year, the model presented by Nelson et al. (2009) estimates that NCA-G electric vehicle battery packs (energy-oriented packs with W/Wh ratios under 5) could cost less than $200/kWh for battery pack manufacturers to produce. It would be necessary for motor vehicle manufacturers to achieve this production cost so they would be able to offer packs at a price of approximately $240/kWh to consumers. This example illustrates a truth for the cost of battery pack manufacture: high volume is very important. If certain battery cell or module designs can serve multiple customers — for cells and not necessarily only passenger vehicles — then low costs can be achieved more readily. Tesla's near-term strategy has been to use high-quality consumer electronics cells from unspecified manufacturers, taking advantage of the existing high worldwide volumes of production of these cells. Other manufacturers — including Nissan and GM — are developing new "large-format" cell technologies with an emphasis on design for use in vehicles.

While Nissan is making clear commitments to produce EVs, other manufacturers are also working on EVs and PHEVs to varying degrees. Chrysler developed a “show car” EV similar to the Tesla Roadster and has recently received a DOE grant to produce 220 PHEV pickup trucks and minivans (Hedgpeth and Wilson, 2009). Ford Motor Company’s (2009) plans are to develop a pure battery electric Transit Connect commercial van in 2010, a battery electric Focus compact car in 2011, and a plug-in hybrid electric vehicle and next-generation hybrid electric vehicle in 2012.

3 POLICIES IN SUPPORT OF PLUG-IN VEHICLES

3.1 U.S. FEDERAL POLICIES AND STRATEGIES

The Federal government is now supporting much more that just research and development (R&D). After almost two years of preparatory work after the bipartisan Energy Independence and Security Act of 2007 (EISA), an evaluation system was set up for loans authorized under the Advanced Technology Vehicles Manufacturing Program (ATVMP) authorized by Section 136 of EISA. A number of loans have recently been approved for makers of batteries, electric motors, and drive components and for developers of a system for recharging electric powered cars.

After a lull of 13 years when the Energy Policy Act of 1992 was passed, the Energy Policy Act of 2005 (EPAct 2005) was passed on August 8. It called for the development of grant programs, demonstration and testing initiatives, and tax incentives that promote the production and use of alternative fuels and advanced vehicles. This legislation was followed soon after by EISA, which for the first time included language supporting incentives for plug-in hybrid electric vehicles. Section 102 required a new fuel economy regulation starting in 2011 that requires light-duty vehicles to achieve 35 mpg fuel economy by 2020. Section 105 authorized loan guarantees for construction of manufacturing facilities for advanced vehicle batteries and battery systems. Section 136 authorized the funding of awards and a direct loan program for original equipment manufacturers (OEMs) and component suppliers that re-equip, expand, or establish manufacturing facilities in the United States to produce qualifying vehicles and components. The period of authorization was 2008–2012.

Section 205 of the Energy Improvement and Extension Act of 2008 (signed on October 3, 2009), which is Division B of the Emergency Economic Stabilization Act (Public Law [P.L.] 110-343), quantitatively specified new tax credits for qualified PHEVs purchased between December 31, 2008, and December 31, 2014 (GPO, 2008). The credit amount varied, requiring a minimum of 4 kWh of battery capacity to realize $2,500 in tax credits and increasing to $7,500 for battery capacity of 16 kWh or more. One of the possible purposes of the maximum of $800 million of qualified energy conservation bonds allowed by Section 301 was to subsidize automobile battery technologies. Many other worthy recipients of the bonds were specified.

It is not until the Feb. 17, 2009, American Recovery and Reinvestment Act (ARRA) (P.L. 111-5) that truly significant funding for advanced vehicle technology, including batteries, was made available (GPO, 2009). Under Energy and Water Development, ARRA provides $6 billion to back loan guarantees. Guarantees were originally *authorized* by Section 1705 of EPAct 2005. A $10 million portion of the $6 billion supports the administrative expenses of the ATVMP. Further, $2 billion was made available for grants for the manufacturing of advanced batteries and components and facility funding awards under this section to manufacturers of advanced battery systems and vehicle batteries that are produced in the United States.

Section 1141-1144, Plug-in Electric Drive Motor Vehicles, modified the qualified plug-in electric drive motor vehicle tax credit. Now, the tax credit will be ended for each manufacturer after 200,000 qualified plug-in electric drive vehicles have been sold by that manufacturer for use in the United States, rather than the previously specified value of 250,000 vehicles for all manufacturers collectively. This tax credit expires December 31, 2014. It is available to any vehicle with a gross vehicle weight rating of up to 14,000 pounds and meeting applicable Tier II emission standards. Earlier credits for heavier vehicles have been eliminated. In addition, separate tax credits for qualified low-speed electric vehicles, electric motorcycles, three-wheeled electric vehicles, and electric vehicle conversions are included. For two and three wheelers, a minimum of 2.5 kWh is required to qualify for a credit, which appears to be the lesser of 10% of the plug-in vehicle's cost or $2,500 for PHEVs with 4 kWh; but apparently there is also a tax credit of $2,500 for two and three wheelers of 2.5 kWh up to 5 kWh. From 5 kWh to 16 kWh, additional credits of $417 plus $417 per kWh in excess of 5 kWh, up to a maximum of $5,000 ($7,500 total), apply. Plug-in conversions can obtain a 10% tax credit, up to $40,000, until December 31, 2011.

With regard to loans and grants, the key criteria originally specified in EISA of 2007 were as follows:

- Manufacturing facilities must be located in the United States.
- Engineering integration must be performed in the United States.
- Loans and grants could be applied to costs reasonably related to re-equipping, expanding, or establishing a U.S. manufacturing facility.
- Costs of engineering integration must be incurred in the United States.
- Loans are not available on a retroactive basis. Past advanced technology investments are ineligible.

As a result of this series of legislative steps, a number of grants and loans have recently been awarded. These are briefly discussed in Section 4.3, Grants and Loans Supporting Lithium Ion Batteries and Electric Drive. See the Alternative Fuels and Advanced Vehicles Data Center (2010; http://www.afdc.energy.gov/afdc/index.html) and original legislation for more detail.

3.2 OREGON'S POLICIES AND STRATEGIES

Oregon is a state that has made a strong commitment to encouraging a reduction of vehicle use by increasing density and reducing urban sprawl. A choice in favor of electrified public transit over highway expansion was made in the midst of the oil price increases of the 1970s. In addition to deciding to spend money on electric rail transit lines instead of adding more limited-access highways in the city of Portland, the state also passed legislation requiring that every city and county establish urban growth boundaries (National Research Council, 2009). A regional transportation planning entity and planning process was set up for the Portland area. Since the mid 1990s, the Oregon portion of the Portland metropolitan area has increased its rate of transit ridership much more rapidly than the population has increased. In 2007, residents of the Portland area inside the urban growth boundary traveled about 17 percent less than the national average. Transit ridership played only a small role. Denser housing development on lots less than an acre in size ─ predominantly for single-family use/purchase ─ was probably a more important factor than transit. The single-family house was hardly abandoned. Portland, however, is not an extreme example regarding increase in density, ranking 24th among the 50 largest urbanized areas from 1990 to 2000 (National Research Council, 2009). Oregon has one registered passenger vehicle per person, so it clearly remains auto dependent (Durst, 2009).

As of February 2009, Portland was the number one city in the nation in terms of new hybrid sales per household, with 12.2 per 100,000 households. This ratio significantly exceeded other major cities where hybrid sales are intense, including in San Francisco (8.8), San Diego (6.7), Los Angeles (6.1), Seattle (4.9), Sacramento and Washington, DC (4.85), Phoenix (4.5), and Denver (4.1) (Durst, 2009, based on R.L. Polk & Co. data).

Oregon is now among leading states with respect to organized support for plug in vehicles. According to the Oregon Department of Transportation Office of Innovative Partnerships and Alternative Funding (2009b):

> Oregon is poised to lead the nation in the early adoption of plug-in electric vehicles and having one common, open system for charging all types of vehicles is an important factor in making the transition successful. This effort will help gain public recognition and consumer confidence in the EV charging infrastructure by providing uniform performance and safety features throughout Oregon.

The State Building Codes Division has adopted a code on EV charging stations, 17 of which are in place. The code will be revised for the next wave of charging stations. The Governor has issued an Executive Order on Alternative Fuel Infrastructure, encouraging development of infrastructure to coincide with introduction of greener vehicles. A working group has been established by the Governor's office, focusing on infrastructure for EV introduction (Durst, 2009).

Consistent with the 1970s establishment of urban growth boundaries at the state level, the state of Oregon plans infrastructure rules to pre-empt local regulations. Standards for permitting and inspection have been established for EV charging infrastructure. It is anticipated that the next building code update (2010–2011) will specify codes for plug-in vehicle charging infrastructure installations in new homes and other buildings. The Oregon Department of Transportation is working on an installation manual for electric vehicle supply equipment for both residential and commercial sites (Durst, 2009). The commercial site draft is on the Web (Oregon Department of Transportation, 2009a). It presently anticipates that Level 2 commercial, public, and fleet use chargers will operate at 240 V, with 32–70 amps of current and a 40-amp circuit breaker. The 40-amp circuit breaker jumps past the 220V, 15–amp, 3.3-kW charger option for the Volt, recently mentioned by Weverstad (2009) (see Chapter 6, Infrastructure – Generation, the Grid, and Local Distribution). However, the draft does not use the word "residential." It appears that the Oregon Department of Transportation (2009b) is finalizing codes to support EVs ahead of codes for PHEVs in residential applications (2010–2011).

According to Durst (2009), Oregon has had a $1,500 incentive for HEVs in place since 2000, which may explain in part the fact that Portland has the highest sales of HEVs per capita in the nation. This incentive has now been made available for plug-in vehicles. Combined with Federal credits, Oregonians can enjoy subsidies of up to $9,000 for a 16-kWh or higher plug-in vehicle. Businesses are eligible for a credit of up to 35% of the incremental cost of plug-ins. There are also tax credits for "charging devices" available to both businesses and individuals.

3.3 CITY OF VANCOUVER, BRITISH COLUMBIA, CANADA

The City of Vancouver (2009) has developed a regulatory policy with respect to the development of charging infrastructure in support of plug-in vehicles. The study committee concluded that the costs of chargers are considerably lower if the chargers are incorporated into new buildings as they are being built than if they are added by retrofit:

> Early cost estimates indicate that initial deployment of EV charging infrastructure for 10% of the parking stalls, with allowance for future upgrades, would cost less than 0.5% of the building cost.

Although specific dollar estimates were not provided in the committee report to the City, three Vancouver Electric Vehicle Association (2009a) summary statements are quite remarkable with respect to the estimated costs of retrofit (even with advance preparation) versus new installation. Three bullets from the Vancouver Electric Vehicle Association (2009b) letter amended to the report follow:

- The cost to install 100% now with smart load control is only about 30% more than installing 10% now, plus rough in.

- The cost to install 10% of the plugs, plus rough in now, costs almost three times as much per plug initially.

- The cost to install 10% of the plugs is almost one-third of the cost of 100% installation.

Transformer costs were apparently included in the evaluation. The Vancouver Electric Vehicle Association criticized the cost estimates of the City, on the basis of the method of sizing the transformer, arguing that it assumed all charging "on-peak," ignoring the benefits of smart charging (Vancouver Electric Vehicle Association, 2009a). The committee estimated that a parking spot in Vancouver costs $30,000, stating that the Vancouver Electric Vehicle Association had estimated the cost of a charger for that spot would be $1,500 (City of Vancouver, 2009). Ironically, the Vancouver Electric Vehicle Association said the $1,500 estimate was the City's ─ and was high, because all plug-in vehicles were (clearly incorrectly) assumed to plug in at exactly the same time, at the point of peak electrical demand. The City's committee clearly did say that the cost of installing chargers for 10% of parking spaces, with allowance for future upgrades, would be less than 0.5% of the building cost. The recommendation of the committee was that the regulation apply to multi-unit residential buildings.

On July 10, 2009 (Abuelsamid 2009), the City of Vancouver voted to require 20% of new parking stalls to incorporate EV chargers. Costs per charging station were anticipated to range from $500 to $2,000. Developers have 18 months before the requirements come into force, at which time both the electric vehicles and the SAE J1772 Level 2 standards-compliant charging equipment will be available (see Chapter 6 on Infrastructure).

The report to the City of Vancouver said that plans were being pursued to also develop and implement "a strategy to provide incentives for the retrofits of existing buildings with charging infrastructure as the market for EVs increases" (City of Vancouver, 2009).

The stated motivation of the City of Vancouver was to deliver benefits to the city from reducing greenhouse gases (GHGs). The utility providing electricity to Vancouver, BChydro, predominantly draws its power from hydroelectric generation.

4 STATE OF BATTERY TECHNOLOGY ─ CHEMISTRIES ENABLING ELECTRIC DRIVE

4.1 NICKEL METAL HYDRIDE

NiMH batteries were offered in many of the EVs produced and marketed in the 1990s. Although those EVs did not succeed commercially, from 2000 until now, NiMH enabled electric drive to get a reasonably successful start in HEVs, with Toyota taking the lead with the Prius HEV. David Hermance (2006) of Toyota reported that in the state of California, Toyota had spent $9,615 per electric vehicle sold (e.g., RAV4 SUVs) on advertising, compared to $567 per Prius HEV sold. He detailed the advertising efforts and market responses. The EV was predominantly leased and used in fleets, while 98% of the Prius HEVs were purchased outright. The cost of the RAV4 EV, including charger, was $42,000, while the cost of a Prius was about half as much. EV lessors and purchasers were overwhelmingly male, while Prius buyers were female somewhat more often than they were male. Hermance emphasized the cost effectiveness of the HEV over the EV.

The Prius is by far the leading-selling HEV and is still using NiMH. Its second U.S. generation (third Japanese generation), the version introduced in the United States as a 2004 model, included internationally (but not in the United States) a switch that would enable the owner to operate the vehicle only electrically for short distances at low speeds ─ perhaps between 1 and 2 kilometers. This switch (now available in the generation three 2010 model) was not made available on 2004–2009 U.S. models, but it was then available in Japan and Europe. <u>However</u>, the electronics supporting the switch did exist in 2004–2009 U.S. models. The Prius did not have a plug. Its ability to operate electrically depended on the charge of the battery provided by the engine and/or regenerative braking.

4.2 LITHIUM-ION

The availability of the electronics to allow all-electric operation in the 2004 generation of the Prius led Felix Kramer, and a team of electric drive proponents to "hack" the system, demonstrating that a larger battery (lead acid) could be installed with a plug, and the Prius could become a "plug-in" HEV ─ a PHEV (Green Car Congress, 2004). This battery switch was not approved or condoned by Toyota. Once this conversion was demonstrated, multiple battery manufacturers and entrepreneurs — generally manufacturers of lithium-ion "iron phosphate" (LFP-G) cells and packs ─ became interested in producing kits to convert the Prius to a PHEV. This chemistry was being commercially developed by multiple companies, one of which ─ A123 ─ had a significant contract supplying batteries for a power tool manufacturer.

Multiple technical strategies were adopted, including use of an LFP-G battery pack to supplement the Prius NiMH pack or replace the Prius battery. These conversions generated considerable attention and demonstrated that significant fuel savings could be achieved. Three different Prius PHEV conversions were tested at Argonne National Laboratory (Carlson et al., 2007; Duoba and Carlson, 2007), with engine operation during charge depletion varying from

15% to 25% of the time. Gasoline consumption results per mile varied from about 40% to 25% of 2010 EPA ratings for the 2007 Prius. Unfortunately, these results are not representative of real-world driving and overstate real-world *percentage* benefits (Gonder et al., 2007; Idaho National Laboratory, 2009). Field tests of 110 Hymotion Prius GCRHEVs so far indicate a 39% reduction in fuel consumption via CD operation in lieu of CS operation in "city" driving (Idaho National Laboratory, 2009), compared to the UDDS test results of 63% (Duoba and Carlson, 2007). For the "highway" field tests the estimated reduction is 32%, compared to the dynamometer Highway cycle test results of 46–48%. *The percentage changes, however, are misleading and not particularly relevant* to a calculation of the merits of being able to operate in CD mode in addition to CS mode, which is made possible by purchasing a PHEV instead of an HEV. In this regard, the average savings rate for the two dyno-tested Hymotion Prius vehicles on the UDDS test cycle was 1 gallon saved per 100 miles of CD operation instead of CS operation. For the 110 field-tested Hymotion Prius vehicles, the estimated average "city" driving savings so far is — 1.0 gallon saved per 100 miles of CD operation! Estimated average savings per 100 miles on the official highway dynamometer tests were lower for the two vehicles tested in 2007, at 0.8 gallons per 100 miles of CD operation. For the 110 field-tested Hymotion Prius vehicles, the estimated savings was a bit lower, at 0.7 gallons per 100 miles (Hymotion is owned by A123). When the type of driving is held roughly constant, these results indicate that fuel savings per 100 miles of operation in CD mode remain relatively invariant to driving behavior, although a decline in fuel savings per mile of operation at higher speeds is indicated. However, taking into account the speed of the two driving cycles – 19.5 mph for the city (UDDS) cycle and 48.2 mph for the HWY – the savings per hour of operation in the city are 0.20 gal, much less than the 0.34 gal (at 0.7 gal/mi) on the HWY.

Even these numbers do not tell the whole story. The gallons-per-100 miles reduction at higher speeds is offset by fact that the Hymotion Prius can travel more miles before depleting (but in less time) on the Highway cycle. The dynamometer test results of Duoba and Carlson (2007) indicate that the distance to depletion for the HWY cycle is greater than for the UDDS for this Prius conversion, by about 31%. Thus, on the basis of the Duoba and Carlson results, the total gallons-saved-per-charge appears to be about the same for UDDS and HWY cycle driving. Charge-depletion distances by driving pattern are not quantified in the Idaho National Laboratory (2009) test results at this time.

The battery power available in the resulting vehicles (21 kW or less) was far lower than what they need to run all-electrically on the UDDS. Thus, these grid-connectable HEVs, according to the logic presented earlier, do not warrant use of the acronym "PHEV" because their ability to operate all-electrically is very limited. There is presently no accepted designation for such HEVs. For purposes of this document, I will retrieve the old term "grid connectable" and call these GCRHEVs, for grid–connectable, retrofitted hybrid electric vehicles. If an OEM were to choose to produce such vehicles, the acronym would be GCHEV. To the best of my knowledge, no OEM intends to promote or produce such vehicles or to warrant retrofits. However, Hymotion offers a three-year pack warranty and will apparently replace Toyota's warranted parts if a Toyota dealer refuses to make an otherwise warranted repair and if Toyota certifies cause of part failure to be attributable to the Hymotion pack (Hymotion, undated). Nevertheless, the possibility for production of such vehicles should not be completely ignored. Subsidies are available for retrofits to 2011, and my reading of the language of the ARRA of

2009 suggests that an OEM GCHEV would qualify for subsidies before and after 2011 (until 2014 or until 200,000 vehicles were sold). If one imagines the worst ─ a major, long-lasting war in the Middle East ─ then this option could very well be marketed very successfully by battery manufacturers for use in used HEVs. Great enthusiasm for the results existed during the time that U.S. gasoline prices reached $4.00, and many individuals who were enthusiastic about the potential of PHEVs have purchased GCRHEV conversion kits for the Prius.

In non-vehicular commercial battery applications since HEVs were first introduced, the broad chemistry designation "lithium-ion" has essentially completely supplanted NiMH. Kromer and Heywood anticipated in a 2007 study that the lithium-ion chemistry for use in electric drive vehicles could be considerably cheaper than NiMH in the future in high production volumes. There are now multiple Li-ion chemistries in various stages of development for vehicle applications. The U.S. Department of Energy is presently funding R&D on four chemistries regarded as promising for near-term PHEV development. These are: Nickel-Cobalt-Aluminum with Graphite anode (NCA-G [$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$/graphite]); Lithium Iron Phosphate with Graphite anode (LFP-G [$LiFePO_4$/graphite]); Lithium Manganese Oxide with Graphite anode (LMO-G [$Li_{1.06}Mn_{1.94}O_4$/graphite]) and Lithium Manganese Oxide with Titanate anode (LMO-TiO [$Li_{1.06}Mn_{1.94}O_4$/$Li_4Ti_5O_{12}$]). NCA-G is a very common chemistry. It is the first to be used in a hybrid rather than NiMH. After years of research and development funded in large part by DOE, the first HEV using NCA-G, the Mercedes Benz S400 hybrid, has been introduced in Europe this year and will come to the United States soon as a 2010 model. It uses liquid thermal management.

4.3 GRANTS AND LOANS SUPPORTING LITHIUM-ION BATTERIES AND ELECTRIC DRIVE

DOE has recently approved grants supporting plug-in technology that total $2.4 billion, of which $1.5 billion is to support battery manufacture, $500 million is for companies making electric motors and drive components, and $400 million to test a system for recharging electric-powered cars. These funds will be matched by the recipients (Hedgpeth and Williams, 2009; Whitten and Trudell, 2009). The grants are part of the $787 billion U.S. economic stimulus measure (ARRA) passed in 2009.

4.3.1 Grants

Recipients of grants and highlights of their projects follow (generally ordered by size of grant funding received):

Johnson Controls, Inc., receives $299.2 million. This award certainly supports NCA-G chemistry, though Johnson Controls has not said it is confined to this chemistry.

A123 Systems will receive $249.1 million. This award supports the LFP-G chemistry. A123 has a contract to supply Chrysler Corporation.

General Motors (Detroit-based) will receive $240 million. GM has said that it will use the LMO-G chemistry in the Chevrolet Volt. GM received $105.9 million for use in a Brownstown Township, Michigan, factory that will produce battery packs for the Chevrolet Volt range-extended electric vehicle.

Dow Chemical of Midland, Michigan, receives $161 million. Dow will work with Kokam of Korea to produce an affordable and advanced superior lithium polymer battery (SLPB).

Ener1, Inc., which has an Indiana-based subsidiary EnerDel with a battery plant prepared to begin production, will receive $118.5 million in grants. This award supports the LMO-TiO battery chemistry.

Ford of Dearborn Michigan receives $92.7 million to make electric drive axles and plug-in hybrid electric vehicles and for other projects.

Chrysler, in Auburn Hills, Michigan, receives $70 million to develop 220 plug-in minivans and pickup trucks.

Nissan's partner Electric Transportation Engineering Corp. received a $99.8 million grant to develop electric-vehicle charging stations in five markets. Nissan said that under the contract, it will make as many as 5,000 of its Leaf electric cars available in those markets (1,000/market).

4.3.2 Loans

Nissan has been granted a $1.6-billion, low-interest loan guarantee for an electric vehicle and battery manufacturing plant in Smyrna, Tennessee. The DOE loan is among the first three loans under the Advanced Technology Vehicles Manufacturing Program or ATVMP, a $25-billion program authorized by Congress under Section 136 of the Energy Independence and Security Act of 2007. Funding appears to have been enabled by ARRA of 2009, which allows up to $6 billion in loans.

Tesla Motors has also been awarded a low-interest loan of $465 million, which it will use to produce the Model S, as discussed in Section 2.4.2.

5 CURRENT MARKET STATUS

5.1 THE IMPORTANCE OF ATTAINABLE MARKET SHARE

Figure 5-1 illustrates that the recent success of electric drive has been accomplished by HEVs, not EVs. The gasoline saved per mile of operation when operating an EV instead of a CV is far higher than when operating an HEV. Unfortunately, EVs have not sold well, so the realized fuel savings has been far greater for HEVs because people chose to purchase them. Hitting the "sweet spot" for PHEVs with respect to the combination of fuel savings per mile and vehicles sold will be a challenge resolved by more research and market testing of alternatives.

It is known that a purpose-designed PHEV ─ the Chevrolet Volt (called an E-REV) ─ is about to be introduced to the market. Other manufacturers are working on PHEVs based on HEVs that they have already produced. Ford and Toyota both are conducting R&D on PHEVs using the split HEV technology. Field tests of the Chevrolet Volt E-REV, Toyota Prius PHEVs, and Ford Escape PHEVs are under way. A commitment to retail sales for the Volt has been made.

A fundamental question that the market appears likely to begin to address in just a few years is whether or not the series powertrain and long range of the Volt will put more useable kWh of capacity and equivalent electric miles of service in the market than the likely lower CD range PHEVs that Toyota, Ford, and other manufacturers appear likely to put into showrooms.

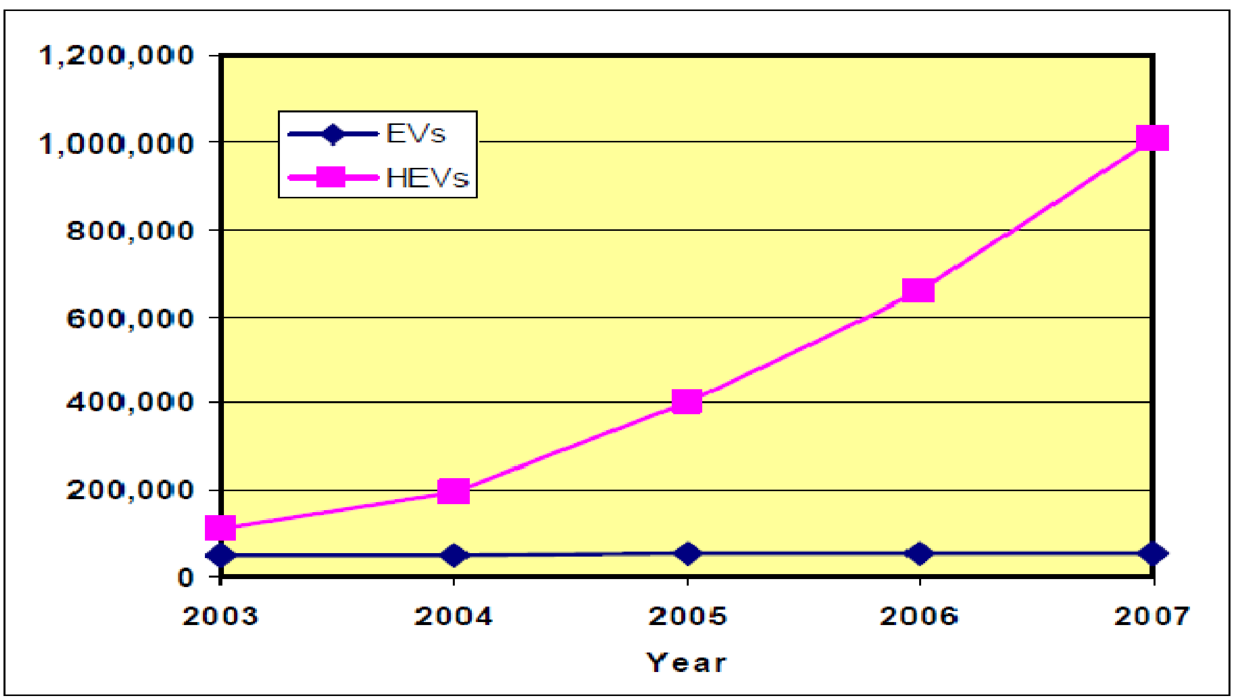

FIGURE 5-1 Cumulative Numbers of HEVs and EVs, 2003–2007

In 2001, Plotkin et al. compared a pure parallel (not presently in the light-duty passenger vehicle market) PHEV20 powertrain and a series PHEV20 powertrain, similar to the Volt. Their finding was that the pure parallel powertrain was both cheaper and more efficient than the series PHEV. Recently, Moawad et al. (2009) simulated and estimated low-volume prices for four plug-in hybrid powertrains, with approximate ranges from 10 to 40 miles. The two with the lowest ranges were PHEVs based on the split powertrain and were labeled in terms of the battery capacity requirements, which were 4 and 8 kWh, respectively, for about 10 and about 20 miles of CD range. The two with the highest ranges were based on the series powertrain and had 12 and 16 kWh of battery pack capacity, respectively. The measure of cost effectiveness used was simple payback assuming one charge per day. The payback calculations indicated that the owner had to regularly use the full capacity of the pack to obtain a reasonable payback. In other words, for a good payback, the driving behavior required for payback involved driving a distance in excess of the CD range. This relationship meant that as the CD range increased, the percent of potential U.S. customers who could obtain a reasonable payback declined. The other finding was that the payback times for the split PHEV10 and split PHEV20 were better (faster) than for the series PHEV30 and series PHEV40.

There are numerous complications and nuances that remain to be explored on paper. In addition, the validity of these estimates will be tested in the marketplace. Nuances are that only the Volt E-REV design will reliably operate in the all-electric mode when driving during charge depletion. This feature may be attractive to consumers and potentially could be demanded by regulators in areas with severe air quality problems. It may be that if consumers and regulators demand reliable all-electric operation during charge-depleting operation of PHEVs at high rates of acceleration, high speeds, and high temperatures, the E-REV will be necessary, even if it is a more expensive way to reduce petroleum use and GHGs.

A few years ago, Dave Hermance of Toyota (2006) discouraged California from requiring all-electric operation of plug-in hybrids because that feature drives up costs. The position expressed on behalf of Toyota was that reducing fuel consumption — while incorporating considerations of vehicle marketability — trumped all-electric range capability. In terms of the definitions used in this document, Toyota appeared to be expressing a preference for either GCHEVs or PHEVs over E-REVs. However, GM's Volt apparently will provide this capability during charge depletion, even though it is not technically required by current regulation. The market will first test how consumers react. California zero emissions vehicle (ZEV) regulations followed GM's announcement in 1990 that it would produce an electric vehicle. However, in the case of GM's introduction of the Volt, there is no evidence that California regulations that force other automakers to produce E-REVs will follow GM announcements. In the meantime, many electric vehicles — the original intent of California's 1990s regulations — are "in the pipeline." It is conceivable that announcements of EV production plans by some manufacturers included some strategic thinking — by moving forward with EVs, they may have protected themselves from the possibility of a general requirement by the California Air Resources Board to require E-REVs from all major manufacturers.

Cost effectiveness comparisons not yet made in the research reviewed here are parallel versus split versus series at the same CD range for different battery power levels. Although the parallel powertrain is not available today in a light-duty vehicle in a full hybrid, Nissan has announced an intention to produce HEVs and PHEVs with a powertrain design that will be different from the one it is presently using (i.e., the split, with licenses from Toyota), with only one electric machine (Loveday, 2009). If so, the implication is that a full hybrid parallel configuration may enter the competition among light-duty vehicle powertrains used for PHEVs or GCHEVs.

In 2009, Honda had not announced any PHEV projects. Honda has developed the "Clarity," which is not a plug-in but a fuel cell vehicle (FCV) that will use a lithium-ion battery pack. Honda planned to lease the Clarity in field tests. Toyota has recently touted a successful long-distance test of its hybrid FCV.

6 INFRASTRUCTURE ─ GENERATION, THE GRID, AND LOCAL DISTRIBUTION

A number of studies have evaluated the adequacy of electric generation capacity to provide for PHEVs. The consistent conclusion is that there is plenty of capacity to support a plausible market for many years. If the market is clearly developing, then these studies also imply that systematic planning for opportunities and challenges from having PHEVs connected to the grid can be implemented readily. Some analysts have estimated that PHEVs and wind will have positive, synergistic interactions (Balash, 2005; Short and Denholm, 2006). Short and Denholm (2006) estimated that if PHEV20s constituted 50% of the U.S. fleet, total electrical generation would increase by 4.4%. Despite a projected 3.9% increase in coal generation, the sum of carbon dioxide emissions from light-duty vehicles and electric generation were estimated to fall by 9.5% because of the sharp reductions in gasoline use. Short and Denholm (2006) also examined a case with a similar market share estimate where sophisticated interactions of PHEV60s and the grid were simulated, with power being shuttled into and out of the batteries of parked vehicles. In this case, with a very integrated system, wind power was strongly supported, actually increasing the generation share by 7.5%, which is above what is required to charge the PHEVs (7.3%). Total carbon emissions for the sum of electric utilities and light-duty vehicles were simulated to drop by 14.7%.

The bottom line is that the grid and the generating units serving it can readily support PHEVs as the market expands, and PHEVs can be readily folded into the utilities' customer base. The primary positive long-term interaction is to flatten the aggregate utility load curve, increasing the average load factor and reducing generation cost. Related to this is an acceleration of replacement of older power plants. The installed generation capacity actually was projected to decrease in both of the cases Short and Denholm investigated. It is important to note that PHEV scenarios do not lead to estimates that existing power plants are retained for longer periods. Rather, the stock of power plants is simulated to "turn over" more rapidly, with broader benefits of average improvement in the overall generating mix (Short and Denholm, 2006; Balash, 2005).

I underlined the word "fleet" in the first paragraph above because it is necessary for the share of new vehicles sold to reach a targeted fleet share with a lead of about a decade. In other words, in the Short and Denholm case, the implications are that 50% of new light-duty vehicle sales would be PHEVs by 2040. This estimate may well be optimistic. Even if it is correct, the market penetration process has to start small and build up over a period of years. Early on, certainly over a time horizon of a decade or so, very little pressure for change to generation and transmission would exist.

In the short-term PHEV market, as implied in the earlier discussion of infrastructure in the discussion of EVs, cost increases will primarily be at the household level, and secondarily, in the event that PHEVs and EVs become popular in several nearby houses, at the level of neighborhood transformers. A recent Nissan statement with regard to the HEV illustrates the household infrastructure problem:

> "You can't just walk into a dealership and drive home with an electric car," says Brian Carolin, senior vice president for sales and marketing at Nissan North America. Buyers first need a permit for a 220-Volt charging box that needs its own circuit. The box will cost $500 to $800, installation from $200 to $1,500, predicts Nissan. A law expiring in December 2010 (but with a good chance at being extended) gives you a $2,000 federal tax credit on the charger, on top of the subsidy for the car. Plus, some federal stimulus money will support financing charging stations in cities like Seattle, Portland, San Diego and Phoenix (Muller, 2009; Coulomb Technologies, 2009).

The problem and opportunity are represented by the ubiquitous 110/120V, 15-amp circuit and plug found in most houses and garages. A higher-voltage 220/240V circuit is sometimes present in the house to support electrical appliances, but even if this circuit exists, it will not always serve the garage, and if it is close by, it may not have a plug located conveniently to the garage. Recently released specifications for the Chevrolet Volt mention a 6- to 6.5-hour charge time with a 110 V/15-amp charger. No higher voltage option is mentioned (Radley Chevrolet, 2008). However, in a presentation to the U.S. Environmental Protection Agency, Weverstad (2009), for General Motors, included a slide with three possible charger and charge circuit power capabilities:

- 1.1 kW, 15 amp, 110V
  - Restricted to at-home use only
  - 9 pm to 9 am, randomized start, charge until full

- 3.3 kW, 15 amp, 220V
  - Restricted to home and work
  - Charge at any time, charge until full
  - Effectively two charges per day

- 6.6 kW, 30 amp, 220V
  - Unrestricted location; wherever you park
  - Charge anytime; charge until full
  - Effectively unlimited charges per day

Summary terminology for charging "Levels" is now common. Level 1 refers to the 15-amp, 110V circuits and associated charging equipment. Level 2 refers to 220V circuits, with varying amperages, and more sophisticated charging equipment, with many capabilities to communicate with the grid, the vehicle, and the corporations serving the PHEV customer. SAE is leading an ongoing effort to develop a standard Level 2 charger coupler (plug) that allows for future evolution of sophisticated electronic exchange of information allowing billing, cost reporting to customers, status reports to manufacturers and utilities, and control of charging. In 2009, this effort was not yet complete. Coulomb Technologies already includes many of these features in chargers that it is successfully marketing across the world. With respect to the SAE J1772 coupling standard under development, a coupling design comparable to that currently manufactured by Yazaki will be used. Up to 70 amps may be possible, allowing higher peak kW ratings than presently planned for the Volt charger. This higher rate capability for Level 2 is supportive of electric vehicles, where faster charging will be advantageous. This type of coupler (plug) is cheaper than the prior favorite. One company has stated that it has a Level 2 residential charging station under development, which "will be equipped with the new SAE standard Yazaki J1772 conductive charging coupler" (BTCPower, undated).

However, one reference noted that the Yazaki coupler type could not support Level 3 charging (California Air Resources Board, 2008). Level 3 refers to 440V systems, or so called fast–charging systems. SAE-sanctioned standardization for such systems is further away than for Level 2 charging.

The U.S. Department of Energy awarded a $99.8 million dollar grant to Electric Transportation Engineering Corporation (eTec), a subsidiary of ECOtality. According to Coulomb Technologies (2009), a partner in this effort:

> The grant will allow eTec to undertake the largest deployment of electric vehicles (EVs) and charging infrastructure in U.S. history. eTec will install electric vehicle charging infrastructure and deploy 1,000 Nissan battery electric vehicles in each of five states: Arizona, California, Oregon, Tennessee, and Washington and install approximately 12,500 Level 2 (220V) charging systems and 250 Level 3 (fast-charge) systems.

This deployment effort works out to about 2.6 chargers per project EV, hopefully more than is necessary. *<u>This project suggests an opportunity for focused Clean Cities programs to provide support to efforts to deploy EVs and/or plug-in hybrids in the areas where the chargers are to be installed.</u>* A rough calculation allows an approximation of projected costs per installed charger when it is assumed that:

- The grant is based on 50% cost sharing, so there is likely ~$200 million in total funding.
- If 5,000 Nissan Leafs, at $30,000 each, plus $1,000 of instrumentation, are delivered, the EVs would cost $155 million.
- A total of $5 million is allowed for data collection and analysis of the experiment, leaving about $40 million for chargers.
- Level 3 chargers cost 4 times as much as Level 2 chargers.

Using an estimate of 13,500 Level 2 cost equivalents (250 × 4 for the Level 3 units), the cost per Level 2 charger would be about $3,000. Morrow, Karner, and Francfort (2008) estimate Level 2 costs of $1,520 and $1,850 per charging spot, respectively, for an illustrative apartment complex and commercial facility (pictorial examples for which look suburban). Electrician labor (@$75/hr) and administrative costs (which are probably higher in major metro areas) are about half the total. Transformer upgrades are not discussed. Undoubtedly, the eTec charger installations will usually be located in urban areas that will probably require not only multiple permits but also trenching and wiring, which will involve digging up and then replacing pavement and sidewalks. The level of sophistication of the equipment on the chargers, including communication to cell phones on charger status (occupied versus available) and rates by time of day and season, will likely be higher than what is needed in many single-family homes and for many utilities that do not plan to adopt time-of-day rates within the next decade.

At the closing session of the Plug in 2009 Conference, Bill Boyce of the Sacramento Municipal Utility District said that recent costs of residential Level 2 charger retrofits were about $4,000, with about half of that amount attributable to the cost of the charger and half to the costs of the wiring, circuit breakers, and associated panel upgrades (Boyce, 2009). For commercial charging stations, he said the cost was about $6,300. Morrow, Karner, and Francfort (2008) did not distinguish between retrofit and new construction in their cost estimates.

Efforts to develop higher-amperage, Level 2 charging capability than has been available in the past to allow chargers with more than 6.6 kW were justified in August 2008 by the California Air Resources Board (2008), partly on the basis of the needs of the then-forthcoming Tesla EV Roadster, with its 52-kWh battery pack. Potential capabilities for power levels of up to 16–19 kW were touted. On the other hand, the desire to keep costs down was cited as a reason for making the Yazaki Level 2+ coupler a better standard (i.e., good enough) than the competitor model, which was designed to be capable of spanning Levels 2 and 3. The Yazaki coupler design has prevailed.

For the Tesla Roadster, which is an EV, both a 120V and 240V charging option, as well as a more powerful one, are mentioned. In 2001 (Graham et al.) and 2002 (Duvall et al.), EPRI's studies evaluated the following: a 1.4 kW, 120V/15-amp; a 1.9 kW, 120V/20-amp; and a 7.7 kW, 240V/40-amp charger (note that the 220V and 240V pair and the 110V and 120V pair refer to the same circuit, where voltage varies between the high and low value). Although the infrastructure costs at the time for the 240V system were estimated to be $1,000, the quotes from Nissan and Boyce above imply that this estimate is low for retrofits of existing dwelling units. While estimating power availability of a given circuit, EPRI appears to have used a factor that takes into account the difference between a circuit's rated (peak) output and its actual output.

If drawing power from the common 110/120V household plug, EPRI's 2001 and 2002 estimates implied that it would take about 15 hours to charge a full-size SUV with 40 miles of all-electric range, 12.5 hours for a midsize SUV, 9.5 hours for a midsize car, and 8 hours for a compact car. The Chevrolet Volt, an efficient compact car, has recently been advertised to charge in 6 to 6.5 hours (Radley Chevrolet, 2008). Weverstad (2009) honed in on the potential advantage of infrastructure upgrades – faster charging in more locations, enabling multiple charges per day:

> "…an infrastructure improvement allowing multiple charges per day is one factor that could allow a reduction in E-REV or PHEV battery size while maintaining similar levels of petroleum displacement and CO_2 reduction."

In addition, higher-rate Level 2 charging would probably be necessary if larger-size PHEVs are to be successfully marketed.

According to Duvall et al. (2002), the 7.7 kW 240V charger would bring the time for charging of a midsize SUV PHEV20 down to 1.1 hours from 6.3 hours. Such a capability would allow full charges to be implemented in many circumstances where the car was parked for work, shopping, or recreation. Suppose that the installed charger cost was $1,500 and could be used an average of about 2.5 times per day. Then the first cost per charge per day enabled would be $600. The alternative would be to stick with Level 1 home charging, purchasing enough capacity to double the range (20 to 40 miles) to compensate for the absence of charging infrastructure. For the midsize SUV, according to Duvall et al. (2002) estimates, optimistically, this capability would require 10 nominal kWh of capacity. Again optimistically, at high volume and in the long term, at $240 per kWh, this approach would result in a cost of $2,400. This approach would often, but not always, cost more than the added infrastructure costs for a fast charger. If the customer did not drive to work but returned to the house frequently (about half of vehicles are used this way on a given day, according to our recent examination of the *2001 National Household Transportation Survey* [DOT 2004]) then a purchase of the higher-voltage circuit could pay off nicely in terms of enabling rapid enough recharges. Alternatively, a recharge time of 1.1 hours would allow a recharge during dinner of (most sizes of) vehicles used for work during the day and for other activities in the evening.

Based on these rough estimates, it appears that investment in infrastructure upgrades that allow multiple charges per day could in some cases be less expensive than extending the range of PHEVs from 20 to 40 miles. The estimates that have been documented here do not justify a sweeping conclusion about the relative merits of Level 2 charger and circuit upgrades versus increased battery pack kWh. The odds are that the trade-off is both location and customer specific, so methods of educating potential customers on trade-offs (when available) could be a valuable capability to study, develop, and make available. The evidence at hand ─ the Volt ─ suggests that achievement of 40 miles of pure, reliably all-electric range in a plug-in HEV (or as GM calls a vehicle with such a capability, an E-REV) is not as simple as assumed in Graham et al. in 2001. The evidence is that achieving 40 miles of range requires redesign of the vehicle to allow acceptable packaging of the battery, particularly if the battery provides all power during peak acceleration. Ignoring vehicle redesign costs, let's construct a rough estimate of the battery pack costs of going from 20 to 40 miles of all-electric range. If battery kWh were to go from 20 to 40 miles, the near-term technical information for the Volt implies that 8 kWh of added nominal battery capacity are required. The average cost of the first-generation pack is anticipated to be $500/kWh (Truett, 2009). The incremental cost of the last 20 miles of capacity for the pack should be less than for the first 20 miles because both the W/Wh ratio and the $/kWh ratio drop (Graham et al., 2001; Kromer and Heywood, 2007; Nelson, Santini, and Barnes, 2009). Therefore, the cost of the first 20 miles is assumed to be $600/kWh, and the second 20 miles is assumed to cost $400/kWh. The cost of the second 20 miles of range capability would be $3,200 (because of the design of the Volt, compared to the SUV discussed in the prior paragraph, the W/Wh value of the Volt pack is higher than for the simulated parallel SUV PHEV pack, making a higher $/kWh value appropriate for the Volt pack). However, in the longer term, the Volt pack costs per kWh are likely to diminish.

The hypothetical $240/kWh battery pack in the SUV example was optimistic for high volumes well into the future and for a PHEV but not for an E-REV. Plug-in SUVs may not be available for years. The Volt, on the other hand, is almost here. The trade-off may vary for different customers. If upgrades to Level 2 charging to enable multiple charges per day were to cost a customer thousands of dollars, such a customer might prefer a PHEV with a longer range or an E-REV small enough to use Level 1 charging and charge overnight, so that only one charge per day would be necessary.

Rated CD ranges achievable in GCHEVs and PHEVs that are options on an HEV ─ not unique vehicles such as the Volt ─ remain to be determined. However, ranges in the 15- to 20-mile area seem possible with simple adaptations of HEV battery packs (Nelson, Santini, and Barnes, 2009).

There is another issue, however. In the GCHEV concept, the blended CD range may be further than it is in a PHEV if the battery used cannot pump out power fast enough to deplete quickly. As Santini and Vyas (2008a) have pointed out, the time-to-depletion factor should be considered in addition to distance to depletion. Up to the point where all-electric operation is achieved, the addition of battery and electric machine power enables shorter distances and times to depletion. Carlson et al. (2007) tests of low electric power GCRHEVs showed that it can take a long distance to deplete. The Carlson et al. (2007) experiments included one Li-ion battery pack with 9 kWh of capacity in a converted Prius. Although the battery pack did fit under the trunk, it eliminated hidden storage space above the space for the spare tire and made it impossible to access the spot where the spare tire was stored. The charge-depletion distance on the UDDS cycle was approximately 50 miles, with the engine on 15% of the time (during accelerations with the engine coming on between approximately 20 and 30 mph). Fuel consumption during charge depletion was reduced by more than 75% (this reduction would not be realized in real-world driving). Not many vehicles are routinely driven more than 100 miles per day, so the possibility for consistently charging such a vehicle twice a day or more is certainly limited. Given the limits of Prius electronics in the generations circa 2004–2009 concerning ability to accept power from the battery pack, this battery must have had no more than 20 kW of peak power capability. It was essentially an energy battery (high specific energy, low specific power), not a power battery (low specific energy, high specific power). Energy batteries are much cheaper per kWh than are power batteries (Nelson, Santini, and Barnes, 2009; Graham et al., 2001; Gaines and Cuenca, 2000). However, at the extreme low end of the power range, they may not be able to discharge rapidly enough in GCHEVs to enable multiple charges per day.

Depending on the plug-in vehicle configuration (E-REV, PHEV, or GCHEV) and size of the vehicle (full-size SUV or aerodynamic compact car), existing infrastructure may be all that is needed (and can be effectively used once daily). For vehicles with fewer kWh in high power packs that are driven many miles per day, return to the house often, and have a garage or carport allowing low-cost charge circuit upgrades (and possibly a neighborhood transformer with spare capacity), Level 2 infrastructure upgrades at the house may be desirable to enable multiple short-duration charges per day. Alternatively, although it may well cost more for total charging capability, Level 2 charging that can be carried out at work, restaurants, retailers, and parking garages could enable plug-in vehicles with Level 1 charge circuits in the garage or carport to charge multiple times per day.

For the EV, the ubiquitous 110V, 15-amp plug alone will clearly be inadequate, and infrastructure upgrades will be necessary. The inclusion of an option for a Level 3 voltage and kW charger for the Tesla S model, and the battery switching concept of Better Place, suggests that very fast charging is seen as necessary for EVs to have a chance to compete with gasoline, ethanol, or diesel for those vehicles being consistently driven at free flow speeds on interstates. *The mix of needs for EV capability to travel nationwide between widely spaced U.S. cities looks expensive, because it involves installation both of expensive fast-charging infrastructure and of infrequently used kWh of battery capacity in the vehicle (i.e., spare capacity for long-distance trips).*

One question for the EV is whether or not Level 2 public charging stations will suffice, or whether Level 3 chargers will be necessary. A Level 3 charger allows a very rapid charge and can give an EV owner a great deal of confidence that if a misjudgment on range has been made, prompt recharging and return to base will be possible. As noted previously, recent experiences with an operating EV fleet by Tokyo Electric Power demonstrated the potential system-wide benefits of two well-placed Level 3 chargers in the territory covered by a fleet of EVs (Anegawa, 2009). TEPCO built two 50-kW, 100-amp fast chargers, and the use of the corporate fleet of EVs jumped, with the remaining SOC upon return of vehicles consistently less than 50%, whereas before the chargers were installed, the vehicles consistently came back with more than a 50% SOC status. The critical fact was that the EV drivers were now comfortable driving further, given the fast charger capabilities and locations. The conundrum was that the fast chargers were not used very often. Though they improved the system behavior dramatically and increased the cost effectiveness of the EV fleet, if they had been required to pay for themselves, an evaluation of the chargers alone would have indicated that they were a failure. There had been Level 2 chargers available before these fast chargers were installed. However, the EV charging time could be hours (at Level 2 rates) and not minutes, so these were not effective. This example clearly shows the importance of judiciously placed public refueling stations and *short refueling times* at those stations for the efficient utilization of EVs. Also highlighted was the importance of the chosen LMO-G laminated cells, which have the necessary capability to absorb the high current of the fast charger. These cells use convective cooling.

Great as they are, Li-ion batteries do not nearly approach the cost effectiveness of liquid fuels for storage of energy. Li-ion batteries enable efficiency in urban driving, offsetting their energy storage penalty. The efficiency advantage closes, however, when the ICE is driven at steady speeds on interstates. Under these conditions, the rapid use of energy per unit time and distance requires that a significant amount of energy be stored, because the vehicle driver generally will remain in the vehicle for much longer periods of time than under "normal" driving conditions/trips and will drive many more miles. Under these circumstances, there is a much greater need to store a lot of energy, so here is where the value premium for high gravimetric and volumetric energy density storage jumps dramatically, and the battery's penalties compared to refined petroleum products or alcohols become acute.

7 LIFE CYCLE ANALYSES ESTIMATES OF "EXTERNAL" DAMAGES OR BENEFITS ─ EMISSIONS, REDUCTIONS IN PETROLEUM USE, GREENHOUSE GASES, AND SUSTAINABILITY

The life-cycle emissions effects of hypothetical PHEVs have been analyzed by Elgowainy et al., 2009; Gaines et al., 2008; Samaras and Meisterling, 2008; Duvall and Knipping, 2007, and Knipping and Duvall, 2007. Different perspectives were used. GHGs were analyzed in the first four. It seems reasonable that, considering the results of the first four studies, one can unequivocally say "with a low carbon electricity system … plug-in hybrids could substantially reduce GHGs as well as oil dependence" (Samaras and Meisterling, 2008). However, this broad statement would also apply for FCVs and EVs under the generic, implausible, and implicit assumption of most Life Cycle Analyses ─ that all vehicles sold will be of the specified type. The other promise of PHEVs is that these vehicles are considerably more feasible economically for the mass market than are EVs (Vyas, Santini, and Johnson, 2009) or FCVs.

To be clear, what is meant here by "mass market" is percent of vehicles sold. When it comes to reducing overall national consumption of refined petroleum products, relatively few vehicles specializing in high daily use and long-distance trips may save the nation a significant amount of fuel. In such applications, FCVs have the ***technical potential*** to fare relatively well against PHEVs ─ if present high costs can be reduced sharply. For the period of time that this document addresses (2010–2015), the FCV is not scheduled to be available commercially. Decisions on commercialization are planned by manufacturers for 2015 (Berretta, 2009; Suckow, 2009; Satyapal and Aceves, 2009; Wipke, 2009; Yokoyama, 2009). However, the competitor that does fill the market space within which the FCV may ultimately best compete (high daily utilization over long distances) is the clean diesel, a powertrain that is now available, as a result of recently implemented emissions reduction technologies. Details on this competition are found in Appendix C, "Engine, Driveline, Body Choices ─ HEV vs. Diesel Powertrain Options for CVs." Among the analyses cited above, only Gaines et al. (2008) considered possible competition from the diesel.

7.1 AIR QUALITY

Only Knipping and Duvall (2007) examined air quality. Relative to other studies, this study had the highest share of coal generation. As far as air quality is concerned, no cases have been examined where carbon controls influence the future mix of power plants. If one believes that such policy is likely, then Knipping and Duvall represent a worst case for air pollution, *when the PHEVs in the market are comparable in CD mode operation to the Chevrolet Volt*. No full fuel cycle emissions or air quality analysis has been conducted under the assumption that the plug-in vehicles are GCHEVs meeting the current Tier II air quality standards, which is the requirement for subsidy under ARRA and certainly will be required by EPA when and if GCHEVs reach high sales volumes. Evaluation of effects of criteria pollutants by means of LCA can provide misleading results concerning the merits of powertrains. Air quality modeling, which is extremely costly by comparison, is necessary.

Ironically, during the 1990s, the motivation for pursuing EVs and then the PHEV option was the potential advantage of zero tailpipe emissions. California regulators tout the program as a success, not because zero tailpipe emissions vehicles (EVs, FCVs) were successful in the marketplace, but because CVs were cleaned up so much in the process (Sawyer, 2006). What has happened is that light-duty vehicle tailpipe emissions have been reduced to such an extent that achieving zero tailpipe emissions by light-duty vehicles does not represent a large change in overall regional emissions (Knipping and Duvall, 2007). Accordingly, achieving the original goal for introducing EVs, PHEVs, or FCVs is no longer of great value. However, the Knipping and Duvall study is reassuring in the sense that it implies that if the evolution of electric drive leads after a few generations of technology to PHEVs that can consistently operate all-electrically at times when air quality is poor, air quality effects are very likely to be consistently positive, though small.

It is important that life cycle emissions effects are tracked consistently for electric drive vehicles to confirm that life cycle emissions remain as low as they do for currently clean gasoline vehicles. While such tracking may not be simple, it is certainly technically feasible. It is possible that technical emissions limits will be a distinguishing factor among the wide range of types of PHEVs and GCHEVs that could emerge due to differences in the necessary control technologies. Longer intervals between engine starts are one concern, as are engine starts during aggressive accelerations. There may be a difficult "no man's land" between blended mode operation where the engine comes on consistently and frequently, keeping the catalyst warm, and pure electric operations, where it never comes on. Some fuel efficiency compromises or after-treatment cost increases may be necessary for some configurations. Electrically heated catalysts, which had long been considered for conventional vehicles, proved to be unnecessary. Perhaps they will be necessary for some PHEV configurations, perhaps not. In any case, the potential for significant region-wide reduction of criteria pollutant emissions is no longer a major factor in the interest in electric-drive vehicles.

Direct effects on air quality are not clear cut and cannot be determined until specific PHEVs emerge and are emissions tested, both off the factory floor and after years of use. The extents to which first-generation PHEVs will result in all-electric versus blended operation and the nature of emissions during blended operation are clearly to be determined. To the degree that the PHEVs are driven all-electrically, Gaines et al. (2008) and Knipping and Duvall (2007) results imply that such driving would reduce ozone precursors. Overall effects on ambient concentrations of particulate matter seem uncertain looking at LCA results alone (Gaines et al., 2008). Nevertheless, because the likely differences in total emissions per mile did not appear to be large, the "displacement" effect (transfer and alteration of emissions in the proximity of roadways to much more remote power plants) seems likely to reduce public exposure to particulate matter, which was the prediction for the United States as a whole in Knipping and Duvall (2007). The Knipping and Duvall study found that the (beneficial) effects of having a massive number of PHEVs operating all-electrically are relatively small compared to all sources of pollution. The Knipping and Duvall work ***implies*** that zero tailpipe emissions operation by light-duty EVs, FCVs, or PHEVs is not an air quality panacea, but could help a little.

The estimates presented to date imply that there are no regional criteria pollutant effects that cannot be addressed successfully. More optimistically, realization of some valuable air quality and human exposure benefits via evolution of the design and use strategies for the technology seems attainable. Low-speed electric operation near sidewalks frequented by pedestrians seems a probable positive achievement for PHEVs and even GCHEVs. Quiet operation in these circumstances is both a blessing and a problem whose trade-offs are under consideration.

7.2 OIL USE AND GHGs

Among the four cited papers that addressed GHGs, three assumed all-electric CD operation. Elgowainy et al. (2009) simulated blended CD operation in vehicles with battery power sufficient to run the UDDS all-electrically nearly all the time. However, by the definition used here, these vehicles would be termed GCHEVs, because each simulated gasoline-fueled HEV configuration used both gasoline and electricity when charge depleting. Three of the four studies assumed that the PHEVs or GCHEVs perfectly replaced the average gasoline vehicle, basing LCA emissions estimates on one annual rate of use consistent across the vehicles. Only the Gaines et al. (2008) study deviated by simulating charge-depleting operations separately and by preparing estimates of emissions per mile of charge-depleting operation for PHEVs and FCVs to contrast with gasoline, diesel, and flex fuel vehicles (FFVs). The Samaras and Meisterling (2008), Elgowainy et al. (2009), and Gaines et al. (2008) studies recognized that future PHEVs might be designed to be FFVs. Each of these three studies implies that if ethanol (i.e., E85) for FFV operation of PHEVs were to come from biomass, then considerably higher annual GHG reductions could be obtained. Related to this implication is the point that to own a PHEV, one in effect also owns a vehicle that is an HEV, which operates considerably more efficiently (except perhaps at rural Interstate Highway speeds) than a CV operates, so the total miles that could be obtained from use of biomass fuels should be extended (Samaras and Meisterling, 2008).

However, Gaines et al. (2008) estimated that if woody biomass were burned in a combined-cycle electric power plant (currently experimental) supporting a PHEV in CD, more urban miles of service would be obtained than if the woody biomass were converted to E85 and used in an HEV. However, for EV (or PHEV CD) operation, a comparison at rural Interstate Highway speeds was not made. At such speeds, it is reasonable to anticipate that the comparison will favor E85 from woody biomass.

The paper by Gaines et al. (2008) focused on developing an understanding of what could be accomplished in the near term (to ~2015) by a hypothetical and highly efficient PHEV, based on the current top-selling powertrain architecture, the split hybrid. The case examined was one where the split hybrid HEV and PHEV designs are structured to enhance fuel efficiency while maintaining functionality for a passenger car suitable for urban use worldwide. However, the evaluation focused on the assumed production and use of such a vehicle in the United States. Unlike other studies, which generally estimate an annualized change in fuel use and emissions for vehicles compared, this study focused on an incremental investigation of what is accomplished by offering a PHEV option as an addition to an HEV.

The ability to operate in charge-depletion mode using grid electricity (i.e., theoretically all-electrically) is what the consumer is purchasing when choosing the PHEV. Therefore, Gaines et al. (2008) separated out the effects of CD operation in their study. This treatment allows one to think in terms of the potential per-mile effects of choosing batteries for PHEVs in lieu of the continued use of conventional gasoline or natural-gas-fueled powertrains, gasoline HEVs, or E85 FFVs or the future use of E85 FFV HEVs, emerging clean diesels, or fuel cell (FC) powertrains. Because the assumption in the study was that the CD mode was all-electric because driving matched the UDDS cycle (not likely for the PHEV designs when driven by average drivers), the CD results also roughly apply to electric vehicles. A caveat that Gaines et al. (2008) warned their readers about (and which is repeated here) was that results could vary by speed of operation. To repeat and reiterate, their analysis unreasonably assumed that CD operation occurred in conservative, "light-footed" urban (city) driving represented by the UDDS cycle. Clearly, additional studies of the behavior of the different types of plug-in hybrids in different driving conditions are desirable.

Unfortunately, evaluation for a single speed, or for a presumed average operation, provides far too narrow a picture for proper understanding of what powertrain types are best used where. The auto industry is arguing this case — advocating a "portfolio" approach that recognizes the varying suitability of advanced and alternatively fueled powertrains as a function of load and/or speed of operation (Berretta, 2009; Suckow, 2009; Satyapal and Aceves, 2009; Yokoyama, 2009). To this pair of distinguishing attributes may be added daily hours of operation. If one also reads the appendices, this document shows that results when comparing diesels and HEVs can shift dramatically when moving from urban to highway driving. In addition, inter-urban interstate highway driving cycles for light-duty vehicles are currently missing from the portfolio of driving cycles from which engineers and scientists can draw. This type of driving accounts for a significant portion of national gasoline use, so this omission is problematic.

Santini and Vyas (2008b) have suggested that the possibility may exist for a relatively stable quantity of fuel saved per kWh of electricity consumed (in comparison to HEV operation), regardless of driving behavior and plug-in technology. An examination of the simulation results of Passier et al. (2007) suggested this possibility. This was also discussed in Section 4.2, examining experimental rather than simulation data. If further investigation proves this possibility to be a reasonable approximation, evaluation of CD electric drive technology could be simplified greatly.

With these caveats in mind, the Gaines et al. (2008) preliminary findings are that for light-duty vehicles that are charge depleting all-electrically in city-cycle operation, due to an anticipated *mix* of natural gas and coal-fired power leavened with a small amount of wind power, PHEVs operating in CD mode will *very sharply reduce oil use per mile and also very consistently reduce GHGs relative to marginal sources of heavy oil feedstocks, in some cases by large amounts.*

Elgowainy et al. (2009) used an estimate of the marginal mix of generation for three regions of the United States that vary widely in share of coal used. Even for Region 4 (MAIN) in the north-central United States, where the marginal generation was estimated to be 75% coal, significant annual GHG benefits of a GCHEV or PHEV were estimated relative to a CV for CD distances from zero (HEV) to 40 miles. However, the annual benefits actually decreased very slightly as electric range increased. Duvall and Knipping (2007), Samaras and Meisterling (2008), and Gaines et al. (2008) each estimated that PHEVs (or, by extension EVs) operating all-electrically would increase GHG emissions *relative to an HEV*. However, Elgowainy et al. (2009), Duvall and Knipping (2007), and Samaras and Meisterling (2008) estimated that the annual operation of the PHEV would significantly reduce GHGs *relative to a CV*. The nuance here is that in order to purchase a PHEV, one in effect purchases the combination of an EV and HEV using a mix of both capabilities. If PHEVs and GCHEVs expand the market for HEV powertrains, which is the explicit argument of Santini and Vyas (2008a) and is the consumer preferences-based prediction in Graham et al. (2001), then *even if coal power is used to provide a majority of the electricity, there will be a net annual GHG benefit of PHEV ownership*, because PHEV purchasers will primarily be buying the PHEV instead of a CV, not instead of an HEV (see Appendix B). Market preference predictions in Graham et al. (2001) imply that if purchases and use of PHEVs or GCHEVs are not widespread, there will be far less overall charge-sustaining operation of electric drive powertrains than there would have been otherwise. This prediction is true if a large portion of PHEVs were to be purchased when HEVs would not. Accordingly, total charge-sustaining operation will be the sum of HEV operations and the portion of PHEV operations that is charge sustaining. Note that in the work of Short and Denholm (2006), in the case where PHEV20s were simulated, use of coal-based electric generation increased but the net system-wide effect of use of the PHEVs, as noted previously, was an overall significant decrease in GHGs.

There have been claims made in the past that the energy required to construct and dispose of batteries would cause so many GHGs that it would make PHEV use increase, rather than decrease, GHGs when the “vehicle cycle” (production and disposal of the vehicle) was taken into account in addition to the fuel cycle. Gaines et al. (2008) examined the relative contribution of battery assembly and disposal on total pathway emissions of HEVs and PHEVs. They estimated the effects to indeed be positive but to be small, even if the battery had to be replaced once in the vehicle’s lifetime. Samaras and Meisterling (2008) also estimated relatively small GHG effects resulting from the battery pack, on the order of 2–5% of life-cycle emissions.

Collectively, the studies examined imply that if a commitment to a low-carbon electric generation future exists, then light-duty PHEVs and EVs can confidently be pursued as a means of sharply reducing both future oil use and greenhouse gas emissions, without a worry that the need to maintain, monitor, and assure low LCA emissions and good air quality will prevent success. If one were to anticipate a revival of coal power in the United States ─ without any successes taking place in technological improvements to coal generation that are in the pipeline ─ then it might be possible to imagine the case in which PHEVs could increase GHGs. This scenario is not likely to unfold, however, especially in light of the recent discoveries of domestic shale-based natural gas in the United States (Yergin and Ineson, 2009; Rotman, 2009). Once Britain discovered natural gas in the North Sea, the nation proceeded to significantly increase the generation of electric power via natural gas at the expense of coal. This strategy seems likely to be repeated in the United States. Certainly, the odds of a strong revival of coal’s share of U.S. generation are significantly diminished compared to a few years prior. As numbers in Gaines et al. (2008) illustrate, the more legitimate concern is that a focus on the diesel powertrain could later make natural gas-to-liquids (GTL) production in support of a diesel fleet more probable as the world runs out of oil, with significantly worse GHG effects than if that same natural gas were used in combined cycle natural gas powerplants to supply a fleet of plug-in vehicles.

7.3 SUSTAINABILITY

Gaines et al. (2008) framed the choice among vehicle powertrain technologies in a way that differed from any of the other studies. The questions asked were as follows: for each fuel feedstock available, what technological pathways exist for converting that feedstock to vehicle miles of service, and which of those options will provide the most miles per unit of energy? The less fuel needed per mile of service, the longer a given fuel resource base will last ─ the more sustainable that resource will be. In the case of renewables, even if a source is renewable, it is economically scarce, so the ability to achieve the most miles from the economically usable resource base remains an important question.

With regard to the desire to use relatively abundant and/or sustainable domestic fuels, the sources of coal, natural gas, farmed trees, and wind/solar are each enabled by PHEVs. Natural gas is included based on recent gas discoveries in shale formations (Yergin and Ineson, 2009; Rotman, 2009). If coal is to be used to create miles of service, Gaines et al. (2008) estimates imply that more miles of service will be obtained by use of CD mode in PHEVs than by use of CTL in CIDI (compression ignition direct injection) engines. For natural gas, it was estimated that combined-cycle natural gas power plants, which are cheap and common, would provide more miles of service in PHEVs operating electrically than if used as natural gas in a compressed natural gas vehicle, or than if converted to liquid distillate (i.e., GTL) for use in diesels. For gasified farmed trees, with the gas burned in power plants, it was estimated that use of CD mode in PHEVs would provide more miles of service per unit of feedstock than would conversion of trees to ethanol for use in HEVs or in PHEVs in charge-sustaining mode. In the case of wind/solar, because of the energy-intensive nature of electrolysis to produce hydrogen for use in fuel cell vehicles, it was also estimated that use of the CD mode in PHEVs would provide far more miles of service than would creation of hydrogen for FCVs. Thus, regardless of which abundant domestic fuel one would wish to use, use of the fuel to serve a PHEV in CD mode would provide more miles of service than the competing options that were evaluated.

Although no single goal should be regarded as the determinant of choice of a fuel conversion pathway, should a goal be to obtain the most miles of service per unit of feedstock, the Gaines et al. (2008) study found that the use of combined-cycle power generation technology providing electricity for PHEV charge depletion was the best option in every case where such a generation technology was considered (coal, natural gas, farmed trees).

Future research should endeavor to explore CD, CS, and annual average operations separately and jointly and in greater detail than is discussed here, including appropriate driving simulations for city, dense suburban, fringe suburban (exurban), local rural, and intercity driving conditions. Particular attention should be paid to determining the best fuel options for inter-city driving conditions for light-duty vehicles, particularly because use of plug-in HEVs will result in distinctly different operations within metro areas than when traveling between them.

8 KEY INFLUENCES ON EARLY DEPLOYMENT IN THE MARKETPLACE

Inevitably, a section on R&D and deployment needs is closely tied to the judgments of the author. It has been shown that there are several technological options for electric drive powertrains and the battery chemistries and designs to support them. Because of an urgent concern that time is of the essence in the effort to develop and deploy electric drive technology, considerable funds have been allocated and spread across many options. The belief that electric drive can now succeed (or that this possibility cannot be ignored because the potential losses in doing so may be great) is a relatively recent development after a few years where EV R&D at the federal level, much less deployment, dropped significantly, and PHEV R&D never really got started. Accordingly, although PHEV research has recently expanded dramatically, many questions remain, and in 2009 no agreed upon and carefully debated and vetted evaluation of PHEV options had taken place at DOE. However, many studies by scientists and engineers in industry and academia and at national laboratories were inspired by the 2001 study by Graham et al. and by the series of coincidental interactions of battery manufacturers and technology advocates working with retrofits of the Prius.

The professional judgments below are those of this author, having reviewed that material, and having worked on evaluations of EVs and/or PHEVs for many years and batteries for a few. Were there a very deliberate and patient evolution of the technology envisioned, many of the steps suggested below would have been undertaken with paper studies or small-sized field evaluations instead of field implementation, testing, and yes, commercialization, of thousands of vehicles using numerous technologies. In 2006, Hermance contended that learning by doing, when a technology is immature, is best undertaken with about 30 vehicles. On the other hand, if there is a rush to learn and to experience and fix the myriad modes of failure of a technology, a much more aggressive effort, which has been put into place, is probably desirable. However, this resource commitment greatly increases the seriousness of the task, since failures can poison consumer attitudes about technologies and set them back for years. Light-duty diesels have succeeded in Europe but failed in the United States because of a rushed attempt to rapidly introduce them in the United States in the late 1970s and early 1980s, the last time oil prices hit recent levels. Admittedly, the circumstances seem considerably worse now, with the United States even more dependent on oil than at the time of the prior and comparably severe oil price shock, with global warming also a significant concern.

8.1 RESEARCH AND DEVELOPMENT NEEDS

R&D needs include the following:

- Conducting field tests in diverse conditions that mimic actual anticipated patterns of use as closely as possible in order to accelerate attainment of a reliably long, real-world calendar life for lithium-based batteries, ideally equal to the life of light-duty vehicles (failing this, rapid inexpensive battery replacement is desirable).

- Widening the useable SOC "window" in PHEVs from 50% to between 70–75%.

- Determining the best and most marketable applications among several competing lithium-based battery technologies.

- Developing the technology to reduce the significant differences between peak and continuous power capabilities of both batteries and motors, which currently makes towing capability by full HEVs, EVs, PHEVs, and FCVs more costly to achieve than other essential performance attributes.

- Determining the best technological pathway to advanced electric drive – what type of plug-in vehicle (EV, E-REV, PHEV, GCHEV) fits where in the market? In other words, when taking marketability into consideration, what charge-depletion distance and powertrain technology will be best in terms of net use of grid kWh via electric drive?

  Questions to be addressed through R&D include the following:

- Is a purpose-built, highly aerodynamic vehicle with low rolling resistance tires (such as the Prius, Insight, and Volt) the best focus, or is the addition of HEV, GCHEV, and PHEV options to vehicles designed primarily for conventional powertrains the best?

- How flexible can battery manufacturing plants be?

  a. Can EV, E-REV, PHEV, GCHEV, and HEV packs (or a subset) be produced at the same factory, with the mix easily altered according to market conditions?

  b. Can multiple chemistries be produced at the same factory?

- Will oil and gasoline prices provide an adequate purchase incentive once vehicles are brought to market? If there is too much uncertainty with respect to the behavior of oil markets, should government tax policy be set to increase predictability for plug-in (and diesel) vehicle producers of future final petroleum product prices to consumers?

- Where is the mass market for various vehicles using electric drive (in the cities, suburbs, or rural areas) and for which type: EVs, E-REVs, PHEVs, GCHEVs, and/or HEVs? What about the mass market for diesels and possibly, post-2015, for FCVs?

- What is the cost effectiveness of charging infrastructure for EVs, comparing the concept of charges for kWh of service based on recovery of costs at each charging point versus packaged service that folds in the leasing of batteries, chargers, and/or charging and incorporating either battery swapping or fast-charging facilities?

- What are the effects of extreme temperatures on various battery chemistries and battery pack designs? Is liquid thermal management consistently necessary, or can thermal management with air frequently suffice? Is automatic active cooling necessary to assure long battery life if electric drive vehicles are frequently parked outdoors on hot, sunny days? Is electrical battery heating desirable in cold climates? At what (cool or hot) temperatures can battery performance be sustained?

- What are the costs versus the benefits of off-peak charging rates and the smart versus simple charging control and timing techniques?

8.2 DEPLOYMENT

Issues to be resolved concerning deployment of these technologies include the following:

- Should simultaneous implementation of new lithium-based battery technologies in HEVs and/or PHEVs, GCHEVs, EVs be pursued, or should HEVs be pursued first?

- How long is the “honeymoon” (or “prove-out”) period for demonstrating reliability before a take-off in sales can be expected? What would the consequences of problems in the planned prove-out period be?

- Can sales and production of batteries at high enough volumes to achieve lowest costs be accomplished and maintained over time?

- Can markets for re-use and re-purposing of batteries be developed to enhance the end-of-vehicle-use value of battery packs, enhancing the economic viability of electric drive (Williams and Lipman, 2010; Neubauer and Pesaran, 2010)?

- Can (1) battery leasing, (2) advance charging infrastructure investment, and perhaps (3) battery swapping set up a virtuous feedback loop, allowing EVs to be marketed in the hundreds of thousands, thereby reducing battery pack costs via high volume and leading ultimately to sales of millions of units?

- How limiting to a successful ramping up of sales is the absence of an experienced supply base capable of mass production of electric powertrain components to be produced in the United States?

- How is the greatest value extracted, given the low power availability for charging in ubiquitous “Level 1” 110/120V, 15-amp household plugs and circuits?

- How significant are costs of upgrades and permits for installation of moderately rapid charging at 220/240V, 15- and 30- (perhaps 40-) amp plugs? How do these costs vary for new construction versus retrofits? How do they vary for single-family homes, walk-up apartments, high rises, and commercial facilities? How do they vary by city, suburban, and rural location? Does climate significantly affect infrastructure cost?

- Will the absence of a charging infrastructure (suitable plugs and meters) at locations next to vehicle parking spots other than in garages and near carports be a deterrent to early implementation of electric drive? For which powertrains? How high a level of charging (Level 2 or 3) in public recharging facilities is necessary for EVs versus PHEVs?

9 LONG-TERM OPPORTUNITIES IN THE MARKET AND TECHNOLOGY DEVELOPMENT NEEDS

For those vehicle manufacturers that have invested in full hybrid powertrains that can be converted to either PHEVs or GCHEVs, there is an opportunity to expand the size of the market by having both HEV and PHEV/GCHEV powertrains available on the showroom floor. More sales spread the research and development costs for drivetrain components other than batteries across a larger number of vehicles, reducing cost per vehicle.

For battery pack integrators, there may be an opportunity to work with emerging lithium-based battery cell and module suppliers in advance to specify attributes that will allow either HEV or PHEV/GCHEV packs to be produced at the same facility, with inherent flexibility to switch back and forth as customer preferences dictate. This production structure could increase the average capacity utilization of the plant, amortizing fixed costs over a higher average output and reducing battery pack costs.

Most utilities do not presently have time-of-day pricing or smart metering capable of real-time control of charging rates (both amperages and cents per kWh). California is leading the nation in the adoption of smart metering. This test case, over the life of first- and second-generation PHEVs, could lead to benefit for the rest of the United States as the technology to implement smart metering is demonstrated and proven (or disproven) in California.

While the short life of first-generation lithium-ion batteries could be a significant impediment to early sales and overall success, it may also be an opportunity. The second generation of batteries could be implemented not only in new but also used vehicles. This deployment could enhance the volume of production of packs and cells in the second generation much more rapidly than if the first generation had a long life. Improvements other than calendar life could therefore be more widespread in the fleet than might otherwise be the case. In particular, if the second-generation SOC window expanded from approximately 50% to about 70%, owners who had purchased the first generation would end up with a superior vehicle in terms of CD range once they purchased their second battery pack.

If the cause of calendar life failure is a slow loss of power and/or energy, which results in promised vehicle performance to drop below specifications, then an option for "failed" batteries could be their re-use in other applications. One that is of significant interest is for storage by electric utilities.

Both HEVs and PHEVs can be designed to accept an option to allow the vehicle to provide back-up power for off-vehicle applications such as those at a residence. In fact, CVs can also be so equipped by adding a generator. However, PHEVs could provide short-term back-up power without engine operation, a slight advantage. The HEV and PHEV already have generators on board, so the cost per kW of back-up power capability should be considerably lower than would be the case for CVs, where the option is seldom purchased. Typically, back-up generators are separate devices left at the house and not carried with the vehicle. Emissions and noise of plug-in hybrid automotive engines would be considerably lower than those of such back-up generators, also a plus.

A more sophisticated but related concept is vehicle-to-house (V2H) generation or battery power capability, a package of technologies at a minimum allowing an HEV, GCHEV, PHEV, E-REV, or EV to temporarily support electrical loads in the house ─ air conditioning seems most obvious ─ in order to accomplish “load shedding” to assist maintenance of electric grid stability. Load shedding involves the utility temporarily shutting off (or reducing) service to a customer for protection of the system. If plug-in hybrids could generate electricity or simply provide charge from the battery to support functions in a dwelling, the utility could temporarily shut off power to such a residence and therefore have considerably greater flexibility in load management. In effect, the plug-in vehicle would function as a limited-function (i.e., no power back into the grid) back-up generator or electric storage device for the utility and/or system operator.

The most sophisticated and complex option of this type is called “Vehicle-to-Grid” (V2G) power, a package of technologies that could allow parked plug-in vehicles to be used to back up the grid or to stabilize fluctuations in electrical load on the grid. Electrons can flow from the vehicle back into the grid, perhaps supporting a load several miles distant. One issue that would need to be examined is the effects of such use of the batteries on warranties. It was noted earlier that there is a possibility that Li-ion may have very good cycle life when the battery operates in a well-controlled environment; however, the calendar life of the battery ─ if the vehicle is parked outside in extreme weather conditions ─ may be a significant problem. If so, because V2G would work best with vehicles parked consistently at the same location, the properties of early Li-ion packs and the needs of V2G could match up reasonably well for a small subset of houses where garages have already been designed to be climate controlled. While having this capability is not the basis for a national vehicle market, it could help get a niche started, from which Li-ion could improve and expand.

As vehicles are redesigned under the pressure of tightening U.S. fuel economy standards, careful evaluation of the mix of CV, HEV, GCHEV, PHEV, E-REV, and/or EV powertrains that can be adapted to and successfully marketed in vehicle platforms of differing sizes will be important. Similarly, if plug-in HEVs are projected to have a larger market share than HEVs (consistent with Graham et al. [2001] market share predictions at low battery cost), the most desirable and marketable type of powertrain – parallel, split, dual mode, or series – will deserve attention.

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APPENDIX A: STATE OF BATTERY TECHNOLOGY (FURTHER READING)

A.1 BATTERY LIFE VS. VEHICLE LIFE CONSIDERATIONS

One of the important uncertainties with lithium-ion (Li-ion) battery chemistries – those that are now being used for grid-connectable, retrofitted hybrid electric vehicles (GCRHEVs) and will be used for plug-in HEVs (PHEVs) and electric vehicles (EVs) – is their calendar life. The thinking for PHEVs (see infrastructure discussion in Chapter 6) is that initially they will be sold to households with garages or carports and charged approximately once per day (overnight). On days when the owner of a PHEV gets sick and stays home, goes on vacation or a business trip, or does not use the car on a holiday or weekend day, then the vehicle will not have its charge depleted and will not need to be charged the following night. Taking this into consideration, if a PHEV were charged an average of 325 times per year and the battery life lasted 15 years, there would be 4,875 charge/discharge cycles, which is within the capability of one advanced Li-ion battery module recently tested over about three years in controlled laboratory conditions (Johnson Controls, 2009). This module "failed" because the slow and steady fading of its capabilities reached design limits. It was not a catastrophic "failure." The module remained under test afterwards. However, the other issue is calendar life, and here the present U.S. Department of Energy (DOE) research and development (R&D) goal is to achieve 10 years of calendar life. It may take a few generations of battery cell and pack designs before a battery pack life of 15 years can be reliably anticipated. As noted in the body of the paper, Tesla Motors says that the possible lifetimes for its EV battery packs range from 5–10 years.

If a 10-year calendar life cannot be achieved for a few pack technology generations, then two near-term management strategies are possible. One is to find the portions of the market where vehicles are driven very intensively – at a high number of miles per day – and reach their end of life at 10 years or less anyway, making only one pack necessary. For these vehicles, it would be desirable to charge more than once per day on average to take economic advantage of the probable good cycle life capabilities of Li-ion packs. A second strategy would be to install a replacement battery in the vehicle. However, if the original packs do last about 10 years, few vehicles could make full use of an identical pack as a replacement. The vehicle would be unlikely to have 10 years of life remaining, and probably would also be driven fewer miles per day. Depending on personal preferences, less power might be acceptable to an owner, so a less powerful battery with a shorter calendar life, smaller energy storage capability, and lesser cycle life would be acceptable. One possibility, for example, would be for an original PHEV20 (where "20" indicates the miles of its expected range) to end its life "retrofitted" to a GCRHEV: while it would have no official all-electric capability, it would use considerably less gasoline per mile than it would if the plug and charger were removed and the PHEV20 simply became an HEV for the remainder of its life.

The larger the battery pack and the longer the range of the PHEV, the larger the portion of the cost of ownership attributable due to the pack – and the greater the interest there will be in whether the pack and remaining useful "life" of the vehicle will have comparable expected lifetimes. One strategy to reduce customer concern is to lease the battery, with a guarantee of replacement in the event of performance failure. A company (such as Better Place) takes responsibility for spreading risk across many owners and can refurbish, recycle, re-lease, or sell packs turned in at the end of a lease term or before as a result of failure. At the extreme is the idea of designing electric vehicles exclusively for automatic switching of battery packs, which are leased to the customer by a corporation. This approach does not seem to be a part of Better Place's plans. Battery-swapping stations appear to be for long trips and to help consumers past "range anxiety."

The question is not whether or not PHEVs and EVs will be equipped with Li-ion batteries; rather, the questions are how much more cheaply and effectively can they be made to work, how large will the market become, how much oil will be saved, how much will greenhouse gas (GHG) emissions be reduced, and how fast will these changes take place?

A.2 USEABLE VS. NOMINAL ENERGY STORAGE CAPABILITY OF BATTERY PACKS

The "nominal" rating of a battery pack has generally been used to measure the storage capability, in terms of kWh. In reality, the nominal rating of battery packs does not represent the amount of energy storage that will actually be used by the vehicle. The first version of the Chevrolet Volt will have a battery pack with approximately 16 nominal kWh, but it will only use 8 kWh. The useable kWh is therefore 50% of the nominal. Noteworthy though is the fact that the nominal rating is used under ARRA to determine subsidies.

The assurance of long battery life for nickel metal hydride (NiMH) is part of the reason for success of HEVs. HEV packs were designed to use about 30% of nominal kWh. Using this amount, in turn, proved to allow the packs to last as long as the vehicle. The goal of the DOE battery program is to reliably use about 70% of the nominal kWh of battery packs in PHEVs. Over multiple generations of NiMH packs used in HEVs, the percentage of nominal kWh was increased as the battery packs were improved through experience. Points of failure can be identified during use and fixes developed, and thus the share of nominal kWh can be increased. This process is called "learning by doing" and contributes to reductions in cost and fuel consumption over time.

Another factor is that, for customer satisfaction, the design of the HEV does not require that the battery pack maintain its power rating over the life of the vehicle. The battery pack provides a considerably smaller portion of the total power of the vehicle in an HEV. In fact, the share of power provided electrically is at least as important a distinguishing factor among HEV, grid-connectable HEV (GCHEV), PHEV, extended-range electric vehicle (E-REV), and EV powertrains as is the share of energy provided. Suppose that the peak power available from the battery in an HEV represents 20% of the total for the powertrain. Then, if the battery pack power deteriorates by 20% over the life of the vehicle, the total deterioration in power attributable to the pack will be 4%, which the customer may not notice. Power remaining in the battery may define the end of the battery pack's useful life in the vehicle. In an HEV, a 20% loss in battery pack power might be acceptable, while in an EV, such a loss may not be acceptable. Thus, for the same chemistry, the challenge of providing battery life in EVs may be greater than for HEVs because of potential customer satisfaction issues only. More "power fade" may be acceptable in

HEVs but not in EVs, while for PHEVs, this factor should fall somewhere between the other two.

Yet another factor is the variation in performance of batteries as a function of temperature. At about zero degrees Fahrenheit, both Li-ion and NiMH batteries have hardly any of their power to make available. Thus, until a battery is warmed up, it will not provide rated power. This circumstance is clearly more of a problem in cold climates as the share of power accounted for by electric drive increases. Thus, as one moves from HEVs to PHEVs to EVs, this cold climate problem becomes more serious. Automatic battery heating in cold climates is a possible solution. It is included with the Tesla Roadster. Absent this feature, consumers who have the ability to park overnight in otherwise heated garages would be a preferable initial target market, those who have unheated garages with shared walls with the dwelling are preferred next, those with carports next to dwelling units or free-standing garages are third, and then on-street parking. Some warm-up in midday can be expected in most circumstances, but a morning starting at zero degrees Fahrenheit is likely to be followed with a daytime temperature causing a significant reduction in drive-away battery pack power, once the vehicle has been parked outside. Garages do tend to be more common in cold climates, which compensates somewhat. Electrical heating of battery packs seems the likely long-term solution. In areas with extremely cold climates (predominantly outside of the United States – such as Sweden and Manitoba Canada), there may be an existing infrastructure advantage because of the availability of many parking spots with electrical outlets used to keep engines warm. Nevertheless, until field experience is obtained, it will be difficult to determine the technical options and costs to mitigate cold temperature problems for batteries.

The cold temperature problem for batteries is in addition to other problems related to cold temperatures, requiring extra energy to operate the vehicle. In an EV, the heater may have to be electric (fuel heaters have been tried), the front window defrosting will probably be supported by electric resistance heating, and when there is snow on the roads, the snow will increase rolling resistance (which is relatively more important for an electric vehicle). A PHEV can use traditional approaches to draw heat from the engine, although PHEV engines will likely be smaller and generate less useable heat to help cope with cold temperatures.

State of charge (SOC) is the term used to define whether a battery is full of energy (100%) according to its nominal rating, empty (0%), or somewhere in between. Reliably measuring SOC can be a challenge. Battery deterioration can be accelerated either by "overcharging" or by depleting to a very low SOC. One way that the use of a battery differs from the use of an internal combustion engine is that the power rating of the battery in both directions of flow – in and out – is important, while only output power is important for the engine. Figure A-1 shows results from tests of a used NiMH Ford Escape HEV battery pack and illustrates the point that the input (charge power) and output (discharge power) are different, and that they vary as a function of SOC (U.S. Department of Energy, undated). This chart illustrates that both power ratings begin to drop significantly at about 20% SOC, which helps to explain why this portion of the SOC "window" is not used. To the extent that this generic behavior typifies all batteries, one may expect that it may be challenging to achieve a SOC window of wider than 80%. Note also that the slope of the output power curve becomes steeper from about 30% SOC to 20%, before dropping sharply.

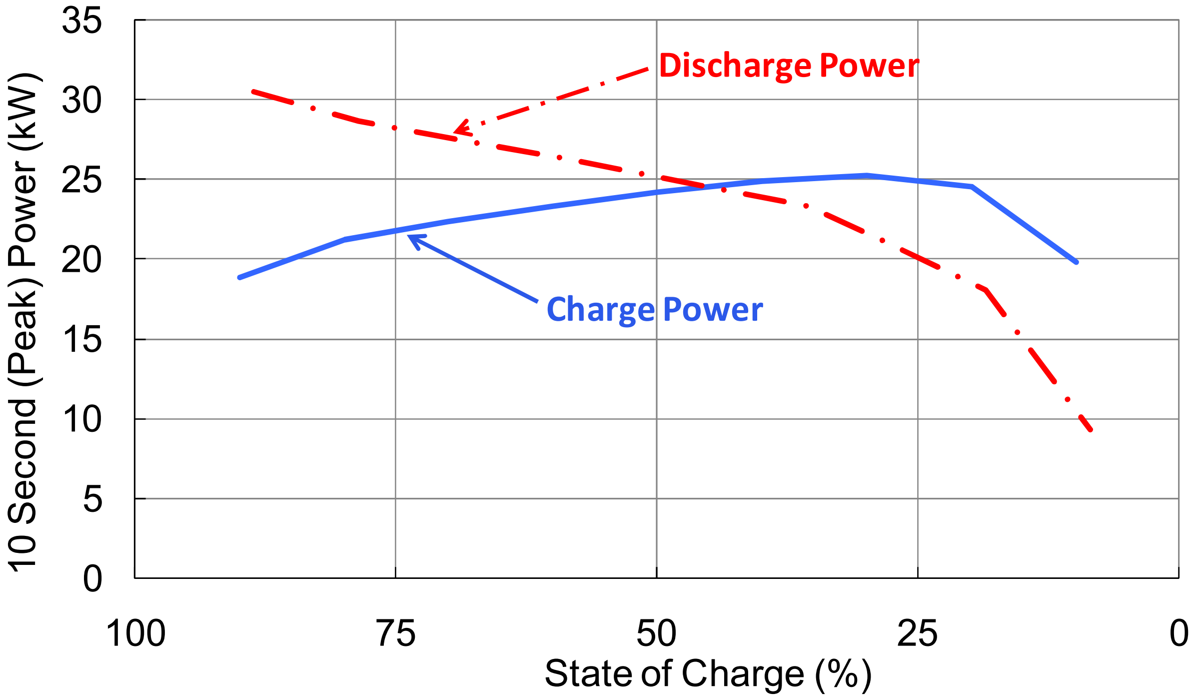

FIGURE A-1 10-Second Input and Output Pulse Power vs. SOC, Ford Escape NiMH Pack (Source: U.S. Department of Energy, undated)

Another important power-related attribute of battery packs that differs from internal combustion engines is that, for a pack, the power available varies significantly, depending on the duration for which power is demanded, while it varies negligibly over the same time periods for an internal combustion engine. The test results for the Ford Escape battery pack illustrate this attribute. Both 10-second and 1-second power ratings have been provided. Selecting 50% SOC as the rating point, the peak output power for 10 seconds is calculated to be 24.9 kW. For one second, the value is 35.3 kW, 42% higher (U.S. Department of Energy, undated). Similar variation is estimated for input (ability to absorb) power.

For HEVs, the operating strategy is generally to hold the SOC window to a region where both input and output power is relatively flat and similar, perhaps 90% to 45% in this case. Figure A-2 is a copy of a chart that is used by the DOE's Energy Efficiency and Renewable Energy Office's Energy Storage Program to illustrate fundamental differences in how batteries are operated in HEVs, PHEVs, and EVs (Howell, 2007). In this case, the generic SOC window for HEV batteries is about 70% to 40%. Combined with the expected 1–2 kWh for an HEV pack, this means that an HEV needs only about 0.3 to 0.6 kWh of energy input and output to function. Because a PHEV operating in charge-sustaining mode will also need only 0.3 to 0.6 kWh and will use a much larger pack (4–16 kWh), the illustrative yellow charge-sustaining (CS) SOC window for the PHEV is much narrower when expressed as a percent of the pack kWh. In the illustration, it looks as if the CS window adjusts from 35% to 25%, an operating "window" of

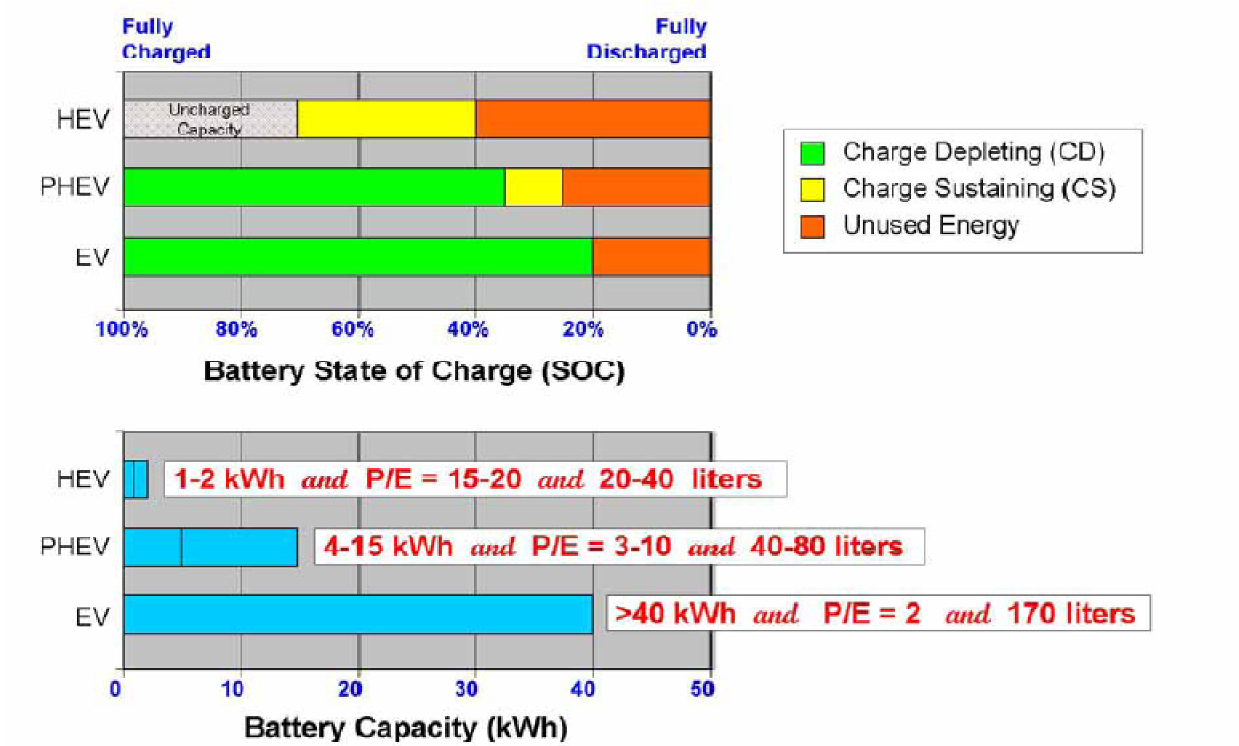

FIGURE A-2 Planned-for Attributes of Battery Packs for HEVs, PHEVs, and EVs in DOE R&D (Howell, 2007)

10%. Assuming 0.3 to 0.6 kWh are needed for CS operation, this result means that the share of the pack kWh needed for the CS operating window ranges from 7.5% to 15% for the 4 kWh case and from 2–4% for the 15 kWh case.

Study of the input and output power profiles as a function of SOC shows that at the PHEV CS operating window, it may be anticipated that in at least some batteries there will be considerably more input power available than there will be output power. This expectation means that if a PHEV is designed to have the same output power as an HEV, the PHEV's battery pack could have considerably more input power available during charge-sustaining operation. If designers take advantage of this capability when it exists, the capture of regenerative braking energy in PHEVs, when operating as HEVs, could be greater for the PHEV. This feature could enable the PHEV to be more efficient than the HEV when in charge-sustaining mode. Working against this potential advantage is the added mass of the PHEV pack. This trade-off will vary by battery chemistry, because the slope and shape of the power curves illustrated above vary by the battery chemistry and materials processing technologies used for a given pack type.

The batteries of HEVs and EVs can be replenished in two ways, while PHEVs can be replenished in three ways. Each vehicle uses regenerative braking to put charge into the battery. Two of the three use an on-board generator powered by the engine, and two use off-board generators via the grid. Problems arise when too much effort is made to push more electrons in near 100% SOC, and when too much effort is exerted to pull electrons out when near 0% SOC.

As 100% and 0% SOC levels are approached, input and output power ratings of the pack diverge, whereas in the middle, the two power ratings will be similar. Damages that can reduce battery lifetime occur when too much effort is exerted, over and over again, to either move electrons out (near 0% SOC) or push more in (near 100% SOC). In practical “capacity” terms, the problem is more serious as the charge of the pack is depleted than when it is full. SOC values above 95% are problematic for some battery chemistries, while SOC values below 20% are problematic at the other end of the range. Thus, the goal of use of 70% of the nominal rating of a battery pack will involve reliably moving from about 95% SOC to 25%. While it may be possible to go beyond these values, it will be very challenging.

The nuance of avoiding charging above 95% in PHEVs and EVs is missing from Figure A-2. A few percentage points of uncharged capacity should be illustrated. A nuance that is captured, however, is the willingness to plan for EV packs to go down to 20% SOC, while PHEV packs are illustrated to go down only to 25%. The frequency with which the pack is operated at or near minimum SOC will be far greater in PHEVs than in EVs. Accordingly, a larger discharge window can be allowed for the EV, because full discharge will be infrequent and the resulting limited damage to the battery tolerable.

APPENDIX B: CURRENT MARKET STATUS (FURTHER READING)

B.1 HEVS AND DIESELS – COMPLEMENTING VEHICLES OR COMPETITORS?

B.1.1 Importance of Distance and Speed Driven

Santini et al. (2009) presented arguments that for vehicles consistently driven at highway driving cycle speeds, a diesel is likely to be a better choice than a hybrid. In effect, the diesel and hybrid were argued to be fundamentally different, suited for distinctly different market niches. This kind of deductive logic has recently appeared in comparisons of fuel cell vehicles (FCVs) to HEVs, PHEVs, and EVs (Berretta, 2009; Suckow, 2009; Satyapal and Aceves, 2009; Yokoyama, 2009). None of these comparisons separated out the diesel engine from the gasoline engine. Generally, in these comparisons, the FCV is argued to be a strong competitor in many of the same market segments now served by the diesel — in vehicles with typically long trips — with HEVs, PHEVs, and EVs argued to be non-competitive for such trips. However, it may be deduced from study of Gaines et al. (2008), Satyapal and Aceves (2009), and Elgowainy et al. (2009 & 2010) that flex-fuel vehicle (FFV) HEVs and FFV PHEVs operating in CS mode on cellulosic biomass-based E85 have far lower GHGs than any fossil-fueled alternative, almost as low as via H_2 production from such biomass to serve FCVs. In fact, these last two options for use of biomass for transportation are so close in GHG terms that other factors — such as cost of implementation — would clearly override the small differences. Thus, although more focused analyses on intercity travel are desirable, it is possible that the FFV HEV and FFV PHEV — by serving intercity travel needs with very low cellulosic biomass E85 GHGs — may expand the market of the HEV powertrain, holding back erosion of the market for long-distance, high–speed, light-duty vehicles in favor of the clean diesel or to the FCV. For now, there is no attempt to work out details of this competition between FFV HEVs (also PHEVs in CS mode), diesels, and FCVs. Appendices B and C are confined to the competition between HEVs and clean diesels. Automakers working to make FCVs succeed do not plan to make commercialization decisions until 2015 (Suckow, 2009; Yokoyama, 2009) or perhaps 2020 (Knight, 2009). However, the omission of careful examination of FFV PHEVs is an oversight, as GM has plans to introduce an FFV version of the Volt within a year or two of its initial introduction in 2010.

For their "FCV absent" comparison of HEVs and diesels, Santini et al. (2009) essentially argued that the diesel and HEV complement each other in reducing petroleum use and are not competitors, as they largely compete for different markets. There it was argued that the plug-in option should give the hybrid powertrain a capability to take a bite out of the diesel's logical market niche. In other words, the plug-in option would expand the logical market share of the hybrid powertrain. In particular, as highway cycle speeds are approached, the plug-in option makes the hybrid powertrain more competitive with the diesel that would otherwise be chosen for its efficiency. An interpretation of these findings was that the plug-in option should create an expansion of the market share of the hybrid powertrain, expanding the market for this type of electric drive. Vyas, Santini, and Johnson (2009) and Moawad et al. (2009) emphasized that the purchaser of a plug-in hybrid must consistently drive further than the CD range of the vehicle to realize a reasonable return on investment. Viewed another way, the further a vehicle is driven each day, the longer the CD range of a suitable plug-in hybrid – and the more easily such a plug-in hybrid's purchase can be justified economically.

Another important factor discussed here is the orientation to date of hybrid powertrains toward front-wheel drive (FWD) (transversally mounted engines) as compared to the diesel powertrain's orientation toward rear-wheel drive (RWD) (longitudinally mounted powertrains).

- Graham et al. (2001) conducted a market preferences study for urban residents. Some findings of interest were:

- The HEV model that was the most highly preferred was the midsize.

- Preferences for HEVs peaked at a "mid-commute" distance and were lowest at a low-commute distance.

- Preferences for PHEV20s did not correspond strongly to commuting distance, but for PHEV60s, preferences increased noticeably for the mid- and high-commute distance relative to the low-commute distance.

When offered a conventional vehicle (CV), HEV, PHEV20, and PHEV60, with four different electric drive costs, the share of urban residents choosing an HEV changed very little as electric drive costs dropped. As electric drive costs dropped, the share of those preferring the PHEV20 first jumped, then stabilized. Preference for PHEV60s rose steadily as electric drive costs dropped. Hybrids (HEVs plus PHEVs) received the largest share of preference at the mid-commute distance, while the lowest share was at the low-commute distance.

These results show that distance driven matters in the choice of powertrain type. The Graham et al. (2001) comparisons, unfortunately, did not include EVs and diesels.

> Santini et al. (2009) addressed the effect of daily distance on the choice of diesel versus PHEV:

We have seen that once the PHEV depletes the battery pack, present day diesels will save more fuel than the PHEV operating in charge sustaining mode. Thus, for kilometers beyond the PHEV's range, the diesel will be the fuel savings winner. The more miles driven per day, the better the diesel will look relative to the PHEV. On the other hand, for those whose choice of the diesel vs. petrol vehicle was difficult because the miles driven per day only barely made the diesel worthwhile, the PHEV may be a better option.

The prediction by Santini et al. (2009) is that the PHEV has the potential to fit into a "niche" between the HEV and the diesel. The quote above refers to the fact that once a PHEV operates in CS mode, it is essentially an HEV, which is less efficient than a diesel is at high average speeds when in the same body design, with tires of the same rolling resistance (the most popular HEV has a more aerodynamic body and lower rolling resistance tires than are available in competing diesels). Thus, the logic extends broadly to GCRHEVs, GCHEVs, PHEVs, and E-REVs. There are multiple strengths of the diesel – fuel efficiency, high continuous torque, and durability. The HEV, GCHEV, PHEV, and E-REV can compete on fuel efficiency but not on high continuous torque. The difference in peak power and continuous power for electric machines and batteries is considerable. Their comparative strength is high efficiency. They have an ability to provide high power intermittently for acceleration, so they work well with lightly loaded vehicles in urban driving. In a demonstration of the difference between an advanced diesel and the Prius in long-distance driving with high average speed in Europe, a *manual transmission* BMW 520d that was 573 pounds heavier and faster accelerating obtained better fuel economy (42 mpg) than a Prius (41 mpg). Some stretches of driving were described as occurring at 78 mph (Howard, 2008).

While this test was an outlier as far as U.S. driving conditions are concerned, the fundamental reality that the fuel efficiency advantage of the HEV powertrain is highly dependent on driving cycle – and decreases as average speed increases – as revealed (Fig. C-3, Appendix C) by data on contemporary U.S. clean diesels and HEVs available at the Web site http://fueleconomy.gov (EPA, 2010). The advantage of the diesel at high average speed and load is inherent. However, the advantage comes in a bundled package. If one does not consistently drive at high average speed, does spend a significant portion of driving in urban and suburban conditions, does not use a vehicle for towing, and is not concerned with high-speed passing acceleration, then such a consumer would be happy to compare a plug-in hybrid to a diesel with respect to the cost effectiveness of reducing fuel use. If such a person also liked driving all-electrically in the neighborhood or beyond, this preference would be another reason to consider PHEVs and/or E-REVs instead of the diesel.

B.1.2 HEV and Potential PHEV Powertrain Types As Compared to the Diesel

The critical point when comparing the HEV and diesel is that one should not compare their potential fuel savings based on their average performance. There are considerable differences in potential fuel savings of the two technologies in "city" versus "highway" driving. Further, the HEV powertrain is typically (though not always) mounted in a vehicle designed to mount the engine transversally in support of FWD, whereas the diesel powertrain is typically mounted in a vehicle designed to mount the engine longitudinally in support of RWD. In both cases, all-wheel or four-wheel drive is developed. HEV is also a broad term that covers several technological approaches, with varying "degrees" of hybridization and varying shifts of city-versus-highway fuel consumption. One set of terms used is "micro, mild, and full" HEV. Based on numbers sold, at this time, the term "full" implies the "split" parallel and series hybrid system originally pioneered by Toyota. However, the dual mode system being sold by GM is also rightfully called a full hybrid. The split system uses two different electric machines (motor-generators) and a totally different transmission than found in other vehicles. Micro and mild hybrids have one electric machine and provide a far smaller portion of total powertrain power via electric traction. The "split" full HEV dominates sales in the United States (see Table 2-1). Toyota HEVs accounted for 76% of U.S. HEV sales in 2008. Ford and Nissan, which used essentially the same system, accounted for another 8%. The dual-mode HEV developed jointly by GM, DaimlerChrysler, and BMW, accounted for 2.4%. Like the split system, this system also uses two electric machines. Each of these vehicles can operate all-electrically at low speeds. The remaining 12% of HEVs sold in 2008 that cannot operate all-electrically were the so-called "mild" HEVs using one electric machine, where sales were dominated by Honda.

There have been no announcements of work on PHEV conversions of "mild" HEVs. Toyota, Ford, and GM all have indicated commitment to developing PHEVs using their current full HEV systems. In addition, Chevrolet has announced the well-publicized "Volt," which is to use a series powertrain and will also have two electric machines and one engine. Until Daimler's sale of Chrysler, DaimlerChrysler had been working on a one-electric machine, RWD, parallel HEV with a plug-in option for the Sprinter light commercial van to be sold through Dodge dealers in the United States.

B.2 FUEL SAVINGS VS. COST OF SELECTED HEV AND DIESEL POWERTRAINS

B.2.1 Interactions with Body Design

On a per-mile basis, "full" (split-type powertrains) FWD split HEVs in CV bodies provide noticeably greater reductions in consumption of gallons of urban fuel (refined petroleum products – gasoline or diesel) (compared to competing conventional powertrains) than does the RWD diesel. However, in highway driving rated by the U.S. Environmental Protection Agency (EPA), this circumstance is reversed, with very significant exceptions – the Toyota Prius and spin-off in the Lexus HS250h, and the Honda Insight. At this time, the only reasonable comparison within the passenger car category of a mass-market diesel to best-selling HEVs is the Volkswagen Jetta against several HEVs. The Jetta has comparable interior volume (91 cubic feet for passengers, 16 for luggage) to the Prius (94/22) and the Insight (85/16). Both the Prius and Insight are vehicles essentially designed around the hybrid powertrain, taking its attributes into consideration.

For a hybrid, as Graham et al. (2001) demonstrated by simulation, significant benefits can be obtained by "load reduction" – reduction in aerodynamic drag and tire rolling resistance. Both changes allow regenerative braking to work more effectively, enhancing the efficiency of the vehicle. The glider load reduction simulated a 16% reduction in gallons per 100 miles of fuel consumption for city driving, and 18% for highway driving when applied to a CV. The comparable effect of the load reduction for the HEV powertrain was 30% in the city cycle and 37% on the highway. This result implies strong positive synergism between the HEV powertrain and load reduction, which is logical because reduction of aerodynamic drag and rolling resistance increase the energy that is retrievable by an HEV during braking. Since no recovery of braking energy is achieved in a CV, this beneficial effect does not exist. In addition, the reduction of aerodynamic drag also offsets the high speed cruise penalty of reduced engine power (engine downsizing) for a hybrid designed to maximize fuel efficiency gains. Graham et al. (2001) estimated that the low load reconfiguration of the body of a full parallel HEV could actually lead to a slightly cheaper full parallel HEV, despite an estimate of a small increase in "glider" (vehicle body) cost. While the cost of the glider was estimated to rise, the reduction in cost of the powertrain, holding certain performance measures at or better than targets, was estimated to more than offset this increase. Given this estimate, the increased reduction in fuel consumption could be regarded as “free.” If this estimate is correct, it implies that Toyota gained a long-term competitive advantage by investing in the Prius.

The late 2009 list price of the automatic transmission Jetta diesel, obtained from the Volkswagen Web site, was $23,370. The Prius comes in four different models, ranging from $22,000 to $27,270. For the Insight, the list price range is $19,800 to $23,100. Admittedly, many factors come into play in setting retail prices, including exchange rates. The Jetta diesel accelerates more rapidly and handles better. But the Prius (though not the Insight) can operate all-electrically at low, neighborhood speeds, a feature that would be of value to some customers.

The other benefit of the aerodynamic body design of the Prius and the Insight is an increase in luggage space compared to optional HEV powertrains in conventional midsize vehicles. According to the Web site http://fueleconomy.gov (EPA, 2010), with each of 2009’s top–selling, car-based hybrids that have both conventional and hybrid powertrains available, there is a loss of luggage space because of the battery pack – Toyota Camry (15 down to 11 cubic feet), Honda Civic (12 to 10), Nissan Altima (15 to 10), Lexus GS (13 to 9). For the 2010 Mercury Milan (comparable to the Ford Fusion), the listed luggage space drops from 16 to 12 cubic feet. In any case, for Toyota and Honda, designing a “dedicated” hybrid vehicle addressed luggage space issues. For the Prius, luggage space doubles that of the Camry HEVs, while for the Insight, there is a 60% increase relative to the Civic HEV.

The Insight is a new model, so it remains to be seen how it will do in U.S. sales relative to the Civic HEV. In 2009 in Japan, in part due to tax restructuring to promote more efficient cars, sales of the Insight led all car models in April, and Honda was increasing production (Lucas, 2009). However, since the third-generation 2010 Prius became available in the United States, sales of the Insight have faltered considerably here (Bensinger, 2009). The Honda Integrated Motor Assist (IMA) mild hybrid system uses about half of the battery power of a Prius and cannot operate all-electrically. It is not very suitable for conversion (or adaptation) to a plug-in version. The Chevrolet Malibu mild HEV, which uses yet another system (the belt alternator system, or “BAS”), is also not suited to running all-electrically. Although mild hybrids are theoretically more economical than are full hybrids with regard to fuel saved per incremental dollar of vehicle cost, if all-electric operation within neighborhoods is a feature that appeals to consumers, these technologies cannot provide it. They are not a path to PHEVs with significant capability for all-electric operations.

The Prius has been in the market for years, and it dominates all other hybrids in total sales. This result suggests in part that the dedicated aerodynamic, low tire resistance option for car-based HEVs is the long-run solution for HEVs. However, if the Insight is not successful in the United States, this result would imply that the type of powertrain – the “split” system first adopted in the Prius – may be the more critical factor. Clearly, as Table 2-1 shows, either interpretation is possible at this time. A decade hence, a more clear distinction may be possible, or other technological options may emerge to become market share leaders.

At the present time, the passenger car customer willing to switch powertrain technologies to reduce fuel use has multiple technological options among HEVs, as well as the advanced “clean” turbocharged direct injection (TDI) diesel. While the clean diesel reduces fuel consumption considerably, the advanced emissions control required has pushed the cost up. The "Tier II" U.S. emissions standards and similar tightening in Europe that have forced the diesel to become much cleaner (Cooper, 2006) have also driven up the price of the diesel (Passier et al., 2007; Smokers et al., 2006).

B.2.2 EPA Comparisons of Diesels versus Hybrids

On a constant vehicle test weight basis, on average, the EPA (2008) *Fuel Economy Trends* report estimates that 2008's cars with diesel engines nominally consume 20–25% less fuel than do conventionally powered vehicles, while hybrid cars consume 30–40% less fuel than do conventionally powered vehicles. Based on earlier discussion, between the leading selling passenger car diesel, the VW Jetta, and the Prius, the latter provides a greater fuel use reduction per dollar of incremental cost. Thus, if reducing fuel consumption cost effectively is a key factor in the decisions of those who compare passenger car diesels and HEVs, Prius-like HEVs should sell considerably better.

Another factor is FWD versus RWD. In the 2008 model year, EPA estimated that 98% of hybrid cars were based on front-wheel drive, while 0% of diesel cars sold were front-wheel drive (EPA, 2008). For two decades, the share of FWD in passenger cars has been above 80%, so the FWD HEVs are well positioned for the typical car buyer, while the RWD diesel is not. Diesel passenger car sales were 1% of hybrid passenger car sales.

Seventy-one percent of hybrid SUVs were equipped with 4WD, and 25% with FWD. Unfortunately, since EPA lumps all 4WD powertrains together, EPA's classification system provides no way to tell what fraction are based on transverse engine mounting (the basis for FWD) versus longitudinal mounting (the basis for RWD). From 2002 through 2008, overall FWD SUV sales rose steadily, more than tripling, while RWD SUV sales dropped by more than a third. SUV hybrids were introduced in 2005. Toyota and Ford HEV SUVs, along with the GM Saturn dual-mode SUV, were all based on platforms with transversally mounted engines (i.e., FWD-based platforms). Unfortunately for GM, the 2008 introduction of three large HEV SUVs based on longitudinal engine mounting (good for towing) came at a time when consumers were shifting away from such SUVs.

No FWD diesel SUVs were sold in 2008. Diesel SUV sales were 20% of hybrid SUV sales, a far higher proportion than for cars. Sixty-five percent of diesel SUVs and 70% of hybrid SUV sales were 4WD. For light-duty pickup trucks and vans of less than 8,500 gross vehicle weight (GVW) (i.e., those subject to emissions testing on vehicle dynamometers), no diesel or hybrid powertrains were sold.

A very important caveat is that the EPA does not include class 2b pickup trucks – trucks from 8,500- to 10,000-lb GVW – as light-duty vehicles. Many diesel engines, combined with 4WD, are sold in this category (Santini and Smith, 2005). The Center for Automotive Research broke out longitudinal and transverse drivetrains within "light"-duty vehicles of less than 10,000-lb GVW. In 2003, the market share of HEVs was about 0.3% and diesels 2.6% (Santini and Smith, 2005). For trucks, all diesels were in the heaviest category (and with longitudinal engines), while all HEVs were in the lighter of the two categories examined, with transverse engines. In the aggregate (cars plus trucks), both HEV and diesel shares were projected to increase from 2003 to 2009, with HEVs achieving a slightly larger share (5%) than diesels (4%), based on unit sales.

According to the EPA (2008), the share of sales of HEVs in the less-than-8,500-lb GVW, light-duty vehicle category was 2.5%. Through May of 2009, Argonne tracking of HEV sales has the share at 2.5%. A factor in this share is likely attributable to the lull before the 2010 Prius came to market. A sharp drop in Prius sales was observed in the months before the 2004 Prius – the second generation – replaced the 2003 model. In fact, Prius sales reportedly did jump in July 2009 compared to June 2009 (by 48%) and to the year prior (by 30%). On the other hand, this total ignores the class 2b trucks (8,500- to 10,000-lb GVW) that were included in the projections of the Center for Automotive Research. Another projection was made in 2004 by Greene et al. As was the case for the Center for Automotive Research, the HEV projections (to 2012) were higher than projections for the diesel. Of the types of HEVs discussed here, a total of 10% of the market was "projected" (the so-called best guess), and 7.2% for diesels.

Because of the collapse in vehicle sales in late 2008 and early 2009 (along with corporate bankruptcies), a number of advanced powertrain technology projects were put on hold or dialed back. Toyota canceled plans to build the Prius in Mississippi. The Saturn VUE dual–mode, plug-in hybrid project was dialed back, as GM sold Saturn. Contracts between Chrysler and Cummins to introduce a Cummins diesel engine were officially canceled as a part of Chrysler's bankruptcy. Ford had reportedly delayed diesel engines until 2013. GM had indicated in 2007 that it was not confident that diesels could succeed in the U.S. market (Freese, 2007). Complicating the decisions on implementation of light-duty diesels is the success of the diesel in the heavy-duty sector in the United States, the rapidity and consistency of which has caused years of more rapidly rising demand for distillate (i.e., diesel fuel) than for gasoline (Bertram et al., 2009). Along with requirements for steep reductions of sulfur in fuel to allow clean diesel technology to work, the increase in highway distillate demand led to increases in highway distillate prices relative to gasoline prices over the last few years.

Another factor that has probably slowed the advance to diesel is the ability to incorporate current technological features of the modern diesel ─ direct injection and turbocharging ─ into gasoline engines (Birch, 2007; Kromer and Heywood, 2007; Osborne, 2007). Osborne (2007) estimated that a new package of technologies for spark-ignited engines would nearly allow them to achieve the low fuel consumption rates of the diesel, while reducing fuel consumption more cost effectively. Kromer and Heywood (2007) also projected the turbocharged direct-injection gasoline engine to be more cost effective in the long run than the diesel. The caveat here is that the comparisons were made for average driving. These studies did not attempt to separate out city, roadway, and limited-access highway driving.

EPA estimates that both hybrids and diesels are more efficient than conventional gasoline-fueled engines in terms of gallons consumed per 100 miles, when vehicle weights are the same. However, only the hybrids are estimated to be significantly more efficient in terms of gallons per 100 miles for passenger cars when holding *interior volume* constant. This seeming anomaly is explained by the fact that diesel passenger cars are RWD vehicles, while nearly all hybrids are FWD. FWD provides more interior volume per unit of vehicle mass. Based on comparison of rear-wheel drive hybrids and diesels tested at 5,500- and 6,000-lb inertia weight, there was no difference between the diesel and the hybrid. At lighter weights, where the diesel is based on RWD and the hybrid on FWD, the hybrid is more efficient than the diesel. On average, among light vehicles of less than 8,500 GVW, diesel vehicles are heavier than hybrid vehicles (EPA, 2008).

If "light duty" is defined as less-than-10,000-lb GVW, then it is quite likely that use of diesels in the United States has saved more fuel in the last decade than hybrids have saved. According to *Fuel Economy Trends* (EPA, 2008), 391,000 diesel engines in light vehicles above 8,500-lb GVW were sold in 2001. In 2008, 312,000 hybrids in the less-than-8,500 GVW category were sold. The diesels were predominantly V8 diesels in pickup trucks (Santini and Smith, 2005) driven in rural areas for many more miles per year than are HEVs, whose engines were predominantly in cars (Table 2-1), the vehicle type with the greatest share in high-density urban areas (Santini and Vyas, 2009). Because diesels are typically driven many more miles per year than are conventional gasoline vehicles, and as they are also sold in larger vehicle types, analysts must be careful not to compare numbers of vehicles sold when trying to estimate the benefits of total national fuel savings of HEVs versus diesels. This same caveat will apply to anticipated benefits of EVs versus HEVs, as we can expect HEVs to be driven many more miles and at higher average speeds than EVs (Santini and Vyas, 2009).

B.2.3 City vs. Highway Driving

The averages used by EPA (2008) in the *Fuel Economy Trends* report reveal one detail, the importance of RWD versus FWD interactions with the diesel and HEV comparison, but miss another detail that is revealed by study of the http://fueleconomy.gov Web site (EPA, 2010). When EPA data are used to examine city fuel economy benefits of hybridization, the benefits are found to be greater than they are for diesels, but when highway fuel economy data are examined, the benefits are greater for diesels than hybrids. Note that this exercise excludes the Prius, as there are no comparable conventional-drive Prius models for comparison.

APPENDIX C: ENGINE, DRIVELINE, BODY CHOICES ─ HEV VS. DIESEL POWERTRAIN OPTIONS FOR CVs

The purpose of this section is to provide graphic, quantitative information supporting the argument that diesels and HEVs should not be regarded as competitors in the United States at this time. Because of its combination of durability and fuel savings, the diesel is used primarily in trucks that are driven many miles per year. Even in cars, when there are two gasoline engine sizes available in the United States, the diesel engine presently is consistently comparable in size (in terms of number of cylinders) to the larger of the two engines. In contrast, in the same circumstance (cars), if an HEV is offered, it will most typically use the number of cylinders in the smaller of the two engines. Compared to CVs, HEVs rather than diesels offer greater fuel savings in city-cycle driving, while diesels offer greater savings in highway driving. The point is that the two powertrains, when considered over the planning period of several years that is relevant to this document, do not directly compete. A recent UBS/Ricardo report contended (Warburton, 2007) that the diesel offers fuel economy that is similar to the HEV at lower cost, *particularly for larger cars and SUVs* (italics for emphasis). This document's discussion, based on U.S. data from two years later, implies that the diesel on the highway cycle offers better (not similar) fuel economy than does the HEV, while earlier discussion of the Prius and Jetta diesel retail prices showed that it does so at about the same (not lower) cost. This investigation also implies that UBS and Ricardo missed the primary use of diesels in U.S. light-duty vehicles – pickup trucks. The diesel already is successful in the United States, but it is not competing in the same market segments where HEVs are succeeding ─ cities and suburbs of major metro areas. Plug-in spin-offs of the HEV are likely to keep the diesel at bay in those segments (Vyas, Santini, and Johnson, 2009; Santini et al., 2009).

For those two-electric machine (split and dual mode) HEVs and diesels available in the marketplace for model years 2009 and 2010, the fuel consumption numbers have been collected from fueleconomy.gov (EPA, 2010). The fuel economy numbers of competing gasoline engines in the same model line have also been collected, and the engine cylinder count has been tracked for each (Figures C-1 through C-4). For passenger car models offering both a gasoline and diesel engine, in no case did a CV gasoline engine have fewer cylinders than the HEV or diesel engine available in the same model line. For diesel passenger cars (i.e., the bottom four vehicles in Figure C-1), the diesel and gasoline engine had the same number of cylinders and about the same (or the same) displacement. No smaller gasoline engines were available. For passenger cars offering both gasoline engines and an HEV (i.e., the bottom seven vehicles in Figure C-2), when two CV gasoline engines were available, the HEV engine was always smaller than the larger of the two.

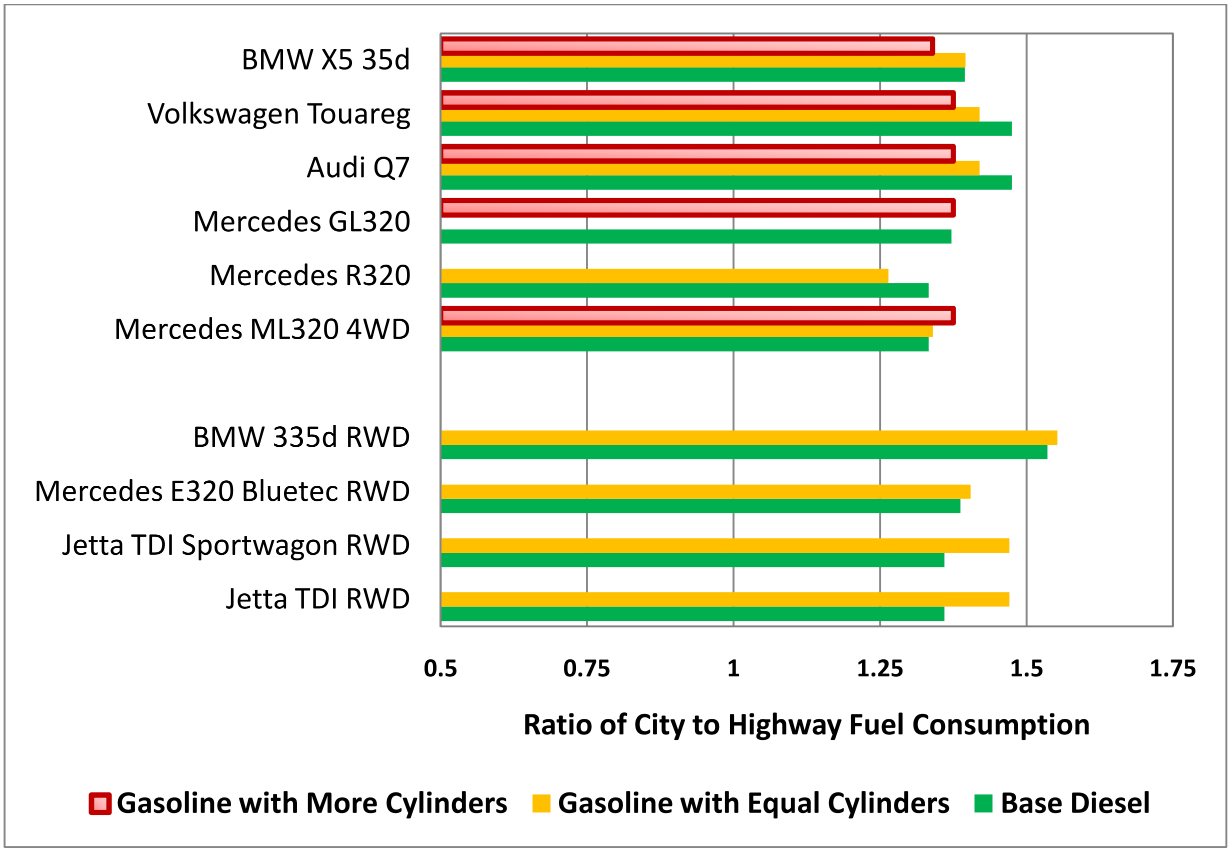

FIGURE C-1 Ratio of City to Highway Fuel Use per Mile for Clean Diesels vs. Alternative Conventional Powertrains in the Same Model Line (SUVs above, cars below)

For SUVs, the strategy that GM employed as compared to other manufacturers stood out. The dual-mode HEV (top vehicles in Figure C-2) was made available with one of the largest engines in the model line. In the case of diesel engines versus their gasoline counterparts, for SUVs there was more often a larger gasoline engine available (top six vehicles in Figure C-1). Thus, in SUVs the diesel has been used so far as a more fuel-efficient option than (for gasoline options) the more fuel-efficient (smaller) alternative gasoline engine. Attaching the HEV powertrain to the larger SUVs and larger engines of those SUVs hampers GM in adapting its dual-mode HEV to a PHEV if a preference for fuel efficiency is an inherent attribute of those seeking hybrid electric drive (Hermance, 2003). GM does have a feature that turns off half of the cylinders in low load conditions, so the GM HEVs straddle power and efficiency to a greater extent than do most other HEV cases where either efficiency or power was emphasized.

As the infrastructure discussion in Chapter 6 illustrated, charging time for large SUV PHEVs would also be an issue, forcing consumers to retrofit garages to provide Level 2 charging capability. Due to the size of vehicle platforms chosen for initial implementation, it seems less likely that existing dual-mode powertrains will be promptly converted to PHEVs than will existing split powertrains. While Ford and Toyota have field tests of PHEVs based on existing HEVs, GM does not. Federal grants could shorten the time it is expected to take before field testing of plug-in powertrains in large vehicles can begin. Chrysler, which has rights to the dual mode, was given funds to develop PHEV pickup trucks and minivans, but not in commercial volumes (220 total vehicles).

A comparison of the city and highway fuel consumption values shown in Figures C-1 and C-2 shows that the ratio for the diesel changes very little compared to gasoline, while for HEVs the ratio drops sharply relative to gasoline. All but one of the split HEVs derived from a FWD drivetrain has a ratio less than 1.00. Every diesel has a ratio above 1.25. The two Lexus car model HEVs (600h and 450h), which are based on RWD platforms, and the GM dual-mode HEVs clearly have a ratio that is higher than it is for the split HEVs based on FWD platforms.

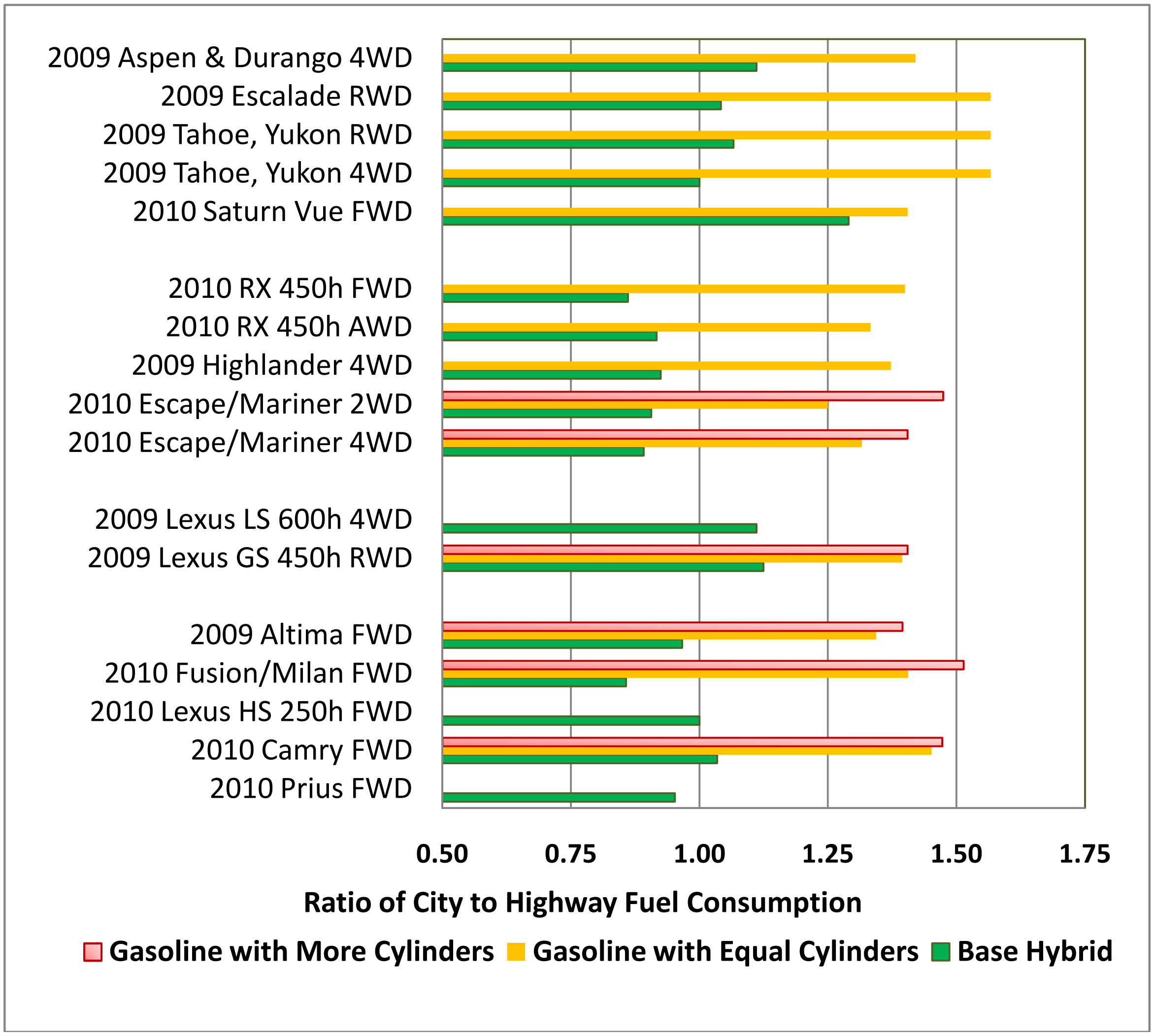

FIGURE C-2 Ratio of City to Highway Fuel Use per Mile for Two-Electric Machine Hybrids vs. Alternative Conventional Powertrains in the Same Model Line (SUVs above, cars below)

Figure C-3 shows that HEV powertrains in standard conventional vehicle bodies do not result in significant savings in highway driving. Savings are usually well below one gallon per 100 miles, where a diesel in city driving in a standard conventional vehicle body would consistently save 1.5 gallons or more on the highway (Figure C-4).

Even if highway cycle speed averages were common within metro areas (they are not), a diesel cannot be converted to a PHEV. *If* the HEVs in Figure C-3 were converted to PHEVs *which ran all-electrically during charge depletion*, then all gasoline use would be eliminated until charge-sustaining operation started. Note that this requires far more battery and motor power than for the GCHEVs being field tested, as discussed in Chapter 2. Generally, in Figure C-3, this finding implies a fuel savings of two or more gallons per 100 miles for split FWD cars in city or highway operation, and 3.5 gallons for SUVs based on FWD platforms, also in city or highway operation. Comparison of these numbers to those plotted in Fig. C-4 shows

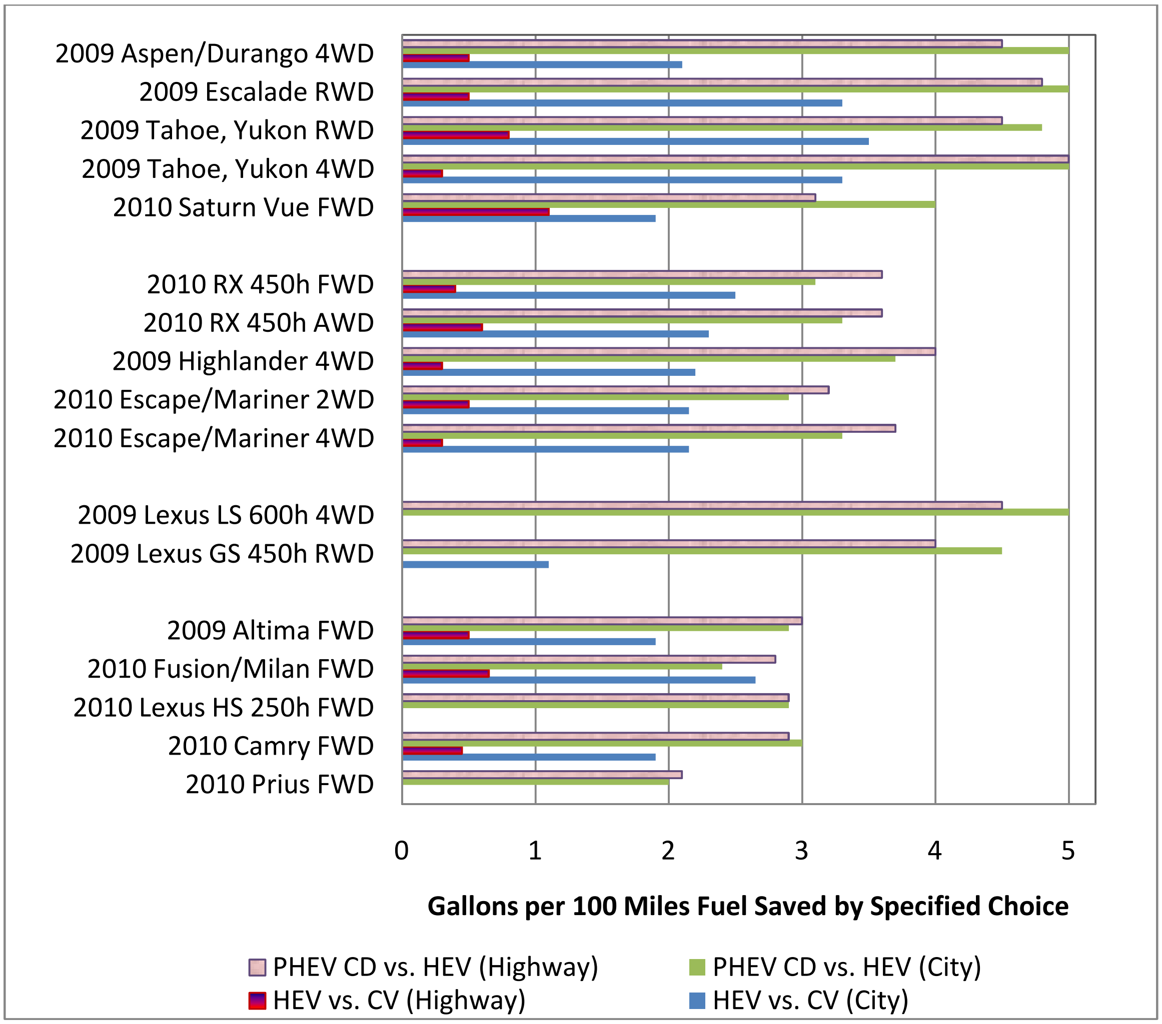

FIGURE C-3 City and Highway Fuel Use Savings: (1) Two-Electric Machine Hybrids vs. Alternative Conventional Powertrains in the Same Model Line, and (2) ZEV Operation vs. Two-Electric Machine Hybrids (SUVs above, cars below)

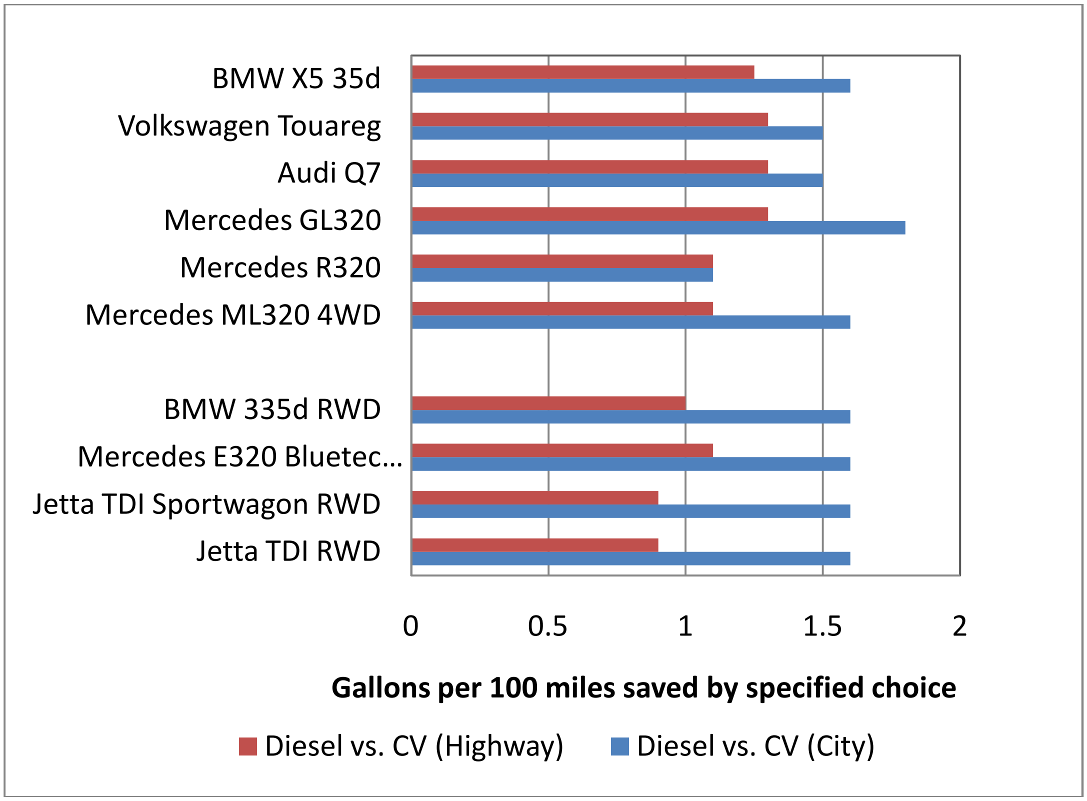

FIGURE C-4 City and Highway Fuel Consumption Savings by Choosing a Diesel

that this presents a greater savings than a diesel, with larger savings in highway than in city driving. Admittedly, consumers will have to pay for electricity and the incremental costs of the PHEV. Suffice it to say that the position of the HEV powertrain relative to the diesel is improved considerably if a PHEV option is available for customers who normally do highway driving. The cost trade-offs merit quantification for GCHEVs, PHEVs, and E-REVs. However, these cost trade-offs have not been quantified in any of the papers cited, and that effort beyond the scope of this document.

The hypothesis that emerges is that PHEVs should make it far more difficult for diesels to compete successfully with passenger cars and smaller light trucks in metro areas. Even so, the recognition that diesels are more likely to be selected in larger light-duty trucks — vehicles that will be driven more miles per year at higher average speeds than will vehicles with electric drive — opens the possibility that light-duty (i.e., <10,000-lb GVW) diesels may still offer as large a petroleum savings to the nation as PHEVs will deliver for the next several years.

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