Hybrid Electric And Fuel Cell Vehicle
Technological Innovation:
Hybrid and Zero-Emission Vehicle Technology Links

Dr. Timothy Lipman*
Executive Director
Center for Interdisciplinary Distributed Energy Research (CIDER)
Energy and Resources Group (ERG)
University of California - Berkeley
2105 Bancroft Way, Suite 300
Berkeley, CA 94720-1516
Phone: 510-642-4501
Fax: 510-338-1164

Roland Hwang
Senior Policy Analyst
Natural Resources Defense Council
71 Stevenson Street, #1825
San Francisco, CA 94105
Phone: 415-777-0220
Fax: 415-495-5996

August 1, 2003

Abstract

While the market for electric-drive, light-duty vehicles is after years of debate and speculation finally beginning to grow and mature in encouraging ways, the mass production of so-called “pure zero-emission vehicles” remains elusive. The current high cost of batteries for EVs and the short driving ranges of these vehicles tend to limit their market appeal, and hydrogen-powered FCVs are not yet ready for widespread commercialization due to the lack of a refueling infrastructure and the relatively high costs of proton exchange membrane (PEM) fuel cell technology and other drivetrain components.

This paper addresses the degree to which continued HEV commercialization is likely to facilitate the commercialization of FCVs by reducing the costs of common electric-drive components and other electric-drive vehicle features. After examining various HEV designs with regard to their commonality with likely future FCV designs, we find that key “break-points” with regard to the degree to which certain HEV designs may help to enable the introduction of “true ZEV” direct-hydrogen FCVs are: 1) the presence of a full-sized motor (though smaller motors of similar types do much to drive down costs of larger motors as discussed below); 2) system voltage levels of greater than 60V that then necessitate compliance with “high voltage” SAE safety standards; 3)

*Dr. Lipman is an associate researcher with ERG as well as a post-doctoral research fellow with the Hydrogen Pathways Program at the Institute of Transportation Studies at UC Davis.
the degree to which the electric motor/generator in the HEV system acts as a traction motor in a continuous sense when needed, rather than simply as an integrated starter generator and/or ICE “drivability smoothing” device; and 4) the prospect of fueling HEVs with hydrogen instead of gasoline and thereby assisting in hydrogen infrastructure development. These break points may be useful in understanding the differences among HEV designs with regard the degree to which each type of design shares common components or other traits with “true ZEV” hydrogen FCVs.

**Keywords:** Electric-drive, fuel cell, hybrid, innovation, technology, vehicle

## 1. Introduction

The market for electric-drive, light-duty vehicles – most notably battery electric vehicles (BEVs), combustion engine/electric hybrid EVs (HEVs), and fuel cell EVs (FCVs) – is after years of debate and speculation finally beginning to grow and mature in encouraging ways. However, the mass production of so-called “pure zero-emission vehicles” (i.e., vehicles with no exhaust or evaporative criteria pollutant emissions such as battery electric or fuel cell vehicles) remains elusive. The current high cost of batteries for BEVs and the short driving ranges of these vehicles have tended to limit their market appeal. Hydrogen-powered FCVs are not yet ready for widespread commercialization due to the lack of a refueling infrastructure and the relatively high costs of proton exchange membrane (PEM) fuel cell technology and other electric drivetrain components. Since the introduction of some “pure ZEVs” is still required in four states in the U.S. that have adopted the California Low Emission Vehicle / Zero Emission Vehicle program, it is critical to the success of these state air quality programs that policymakers find key technology pathways that can accelerate the commercialization of BEVs and FCVs.

From a historical perspective, the electric-drive vehicle (EV) market was initially started with limited success in the early 1990s with the introduction of BEVs in fleets with vehicles such as the Chevy S-10, Ford Ecostar, Ford Ranger, and Toyota RAV4. Although BEV technology has proven to be reliable in fleet service, successful commercialization to the public remains limited. Three of the major automakers have marketed in a limited manner BEVs to the public, including most notably GM’s EV-1, Honda’s EV plus, and Toyota’s RAV4 (first for fleets only and later leased to consumers), and by 2001, about 2,500 battery BEVs were in fleet and private use in California in 2001. [1] This California EV fleet falls far short of the expectations of the early 1990s of air quality regulators, industry suppliers of electric vehicle EV components, electric utilities, and environmental groups. It is clear, though, that the experience in developing electric drivetrain components for battery electrics has assisted automakers in building FCV prototypes. One prime example of this is Ecocar Electric Drive Systems LLC, originally a primary venture of Ford Motor Company and a result of Ford’s program to develop the original Ecostar and Ranger EV electric motor/inverter systems. This company’s three-phase AC electric drive motors are well-suited to FCVs as well as BEVs, and fuel cell manufacturer Ballard Power Systems, originally a minor owner of Ecostar, bought the company from Ford in 2001. Ecostar is now a division of Ballard, producing electric motors and inverter systems for FCV prototypes as well as for BEVs and other traction motor applications.

Today, HEVs are leading the electric-drive vehicle market forward in a dramatic fashion due to the great success of the Toyota Prius and Honda Civic hybrid market introductions in the U.S. and Japan, and of the Toyota Estima minivan and Crown luxury sedan for the Japanese market. In 2001, approximately 40,000 hybrid EVs were sold around the globe, with Toyota accounting for 90% of the market. As of March 2002, Toyota exceeded the 100,000 level of total cumulative
HEVs sold, and based on the first quarter of 2003 appears on pace to see about 60,000 HEVs in 2002. [2]

FCVs appear poised to be the next wave of electric-drive vehicles after HEVs, with commercial introduction inching closer. FCVs are now beginning to be placed with various university and government organizations where they will be tested and used outside of carefully controlled operation by the manufacturers themselves -- as in the past few years with the California Fuel Cell Partnership and demonstration programs in Japan and Germany. Furthermore, hydrogen-powered HEVs are another possibility as a next incremental step after conventional HEVs, where hydrogen use can potentially be introduced in advance of FCV commercialization to begin to gain refueling experience and scale economies in distributed hydrogen production.

This paper examines how a “spillover” or “co-option” effect due to large-scale HEV commercialization is likely to help bring FCVs closer to market by reducing the costs of common electric-drive components. This paper is organized as follow. First, this HEV and FCV design architectures are described. Second, key components/features of HEVs and FCVs that are likely to be shared or linked are discussed, including a few examples of specific commonalities among existing HEVs. Third, the paper discusses how HEV commercialization can reduce costs of specific common components through design innovation, manufacturing learning curves, and economies of scale. Finally, conclusions are reached with regard to the potential for present and future HEV development to help to enable the future introduction of commercial FCVs.

2. **Hybrids as technology pathway to zero emission vehicles**

The early market for BEVs has struggled, and widespread FCV commercialization is still at least several years away. One recent analysis concludes that there is a currently a “deployability gap” that must be closed before successful commercialization of FCVs. The study concludes that three pathways must converge: [3]

1. Engineering development and maturation of fuel cell system stacks and auxiliary systems;
2. Cost reductions of components that are common to all electric drive systems; and
3. Resolution of the technical and infrastructure barriers related to the fuel choice for fuel cell vehicles.

These factors, and the degree to which progress lags or accelerates in each of them, are the key determinants of when FCVs are to be fully mass-produced and commercialized. The challenges for BEVs are analogous, with the current high cost of batteries being the principal barrier.

HEVs are emerging as a key technology that can act as a “stepping stone” to FCV or BEV commercialization by producing a technological “spillover” effect on critical components. The primary reason for this strong linkage is that they are all “electric-drive” vehicles; that is, they derive some or all of their primary motive power from electric motors. Depending on the specific design, HEVs and FCVs share many components that are either the same or closely related, namely electric motors, power inverters/controllers, and wiring systems for high power circuits. This relationship is further strengthened by the likelihood of “hybridizing” FCV designs with battery systems, and this adds batteries and regenerative braking systems to the list of common components.
Another reason why HEVs serve as a useful “stepping-stone” to other EV types is that electric drive components are smaller, and therefore less costly, than for BEVs and FCVs. Hence, the higher, early costs of the relatively novel electric drive products are better tolerated in a HEV market since the incremental cost of the electric drive components is lower than for FCVs. [3]

In terms of advanced vehicle designs, the “spillover” or “co-option” effect is the extent to which the development of technologies for a certain vehicle type and at a particular time can then potentially facilitate or enable the development of future more advanced and environmentally benign vehicle power and propulsion systems.¹ This effect is well known in the development of other technologies. For example the early use of small gas turbines, enabled by their development for aerospace applications, became combined with the more conventional steam turbines to produce more efficient “combined-cycle” power plants. Eventually, the gas turbine part of the combined-cycle power plants became dominant, with a smaller component from the steam-turbine “bottoming cycle.” [4]

Automakers themselves recognize that HEVs provide a technical pathway to FCVs. Thomas Stephens, GM Powertrain vice president at its recent announcement of a new line of hybrids stated that “hybrids are a medium-term bridging strategy to the hydrogen economy.” Stephens noted that GM will “benefit because engineers can use some of the powertrain’s electrical components, such as the software, controllers and electric motors, for fuel cell vehicles.” [5]

Toyota Motor Corporation Chairman Hiroshi Okuda has also argued that HEV development has direct benefits to FCVs, in particular to a hybridized fuel cell vehicle (FCHV). In a recent press release announcing a new hybrid vehicle, Toyota stated the following: [6]

[W]e are well-equipped to meet this FCHV challenge. This is thanks to the extensive knowledge and experience we have gained through the mass production of key hybrid system components - such as motors, inverters, converters, batteries and regenerative brakes - and the acquiring and honing of "power management" skills needed for a successful hybrid formula. All this is largely due to the well-received Prius, which is also sold in Japan and North America.

We are convinced that the principles of Prius’ hybrid technology will be the key to the development of the ‘ultimate eco-car,’” said Okuda, while explaining the potential of hybrid technologies, including the development of FCHVs.

General Motors has made similar statements, including very recent ones. In early 2003, when General Motors announced plans to develop hybrid power systems for more than a dozen models, company president and CEO Rick Wagoner stated that: [7]

[G]iven the present level of fuel prices and consumers’ complex needs and desires, it is uncertain to us just what level of market may exist for hybrids at this point in time. However, we do think the technology has the potential to become a factor in the market. We also see hybrids as a bridge to fuel cells, making these programs of value for developing production drive systems and power controls.

¹ In fact, a 10-part television series for BBC titled “Connections” was developed by James Burke in 1979 and seen by millions of people, with the theme being exactly this sort of technological evolution/co-option and numerous examples given.
Statements such as these demonstrate that automakers are not only well cognizant of the technological linkages between HEVs and FCVs, but are justifying their research, development, and commercialization of HEVs, at least in part, because of the potential benefits to the ultimate commercialization of FCVs. How this step-wise evolution of hybrids to fuel cells lowers the risk of advanced vehicle technology development is laid out explicitly in a recent analysis for the United Kingdom. [8] This report is of particular interest since it is done by Ricardo Consulting Engineers, a well-known consulting firm to major automakers.

3. **Overview of hybrid and fuel cell electric vehicle designs**

Hybrid electric, battery electric, and fuel cell electric vehicles all belong to the same family of vehicle designs known as “electric drive” vehicles. These vehicles derive some or all of their motive power from electric motors. FCVs, like BEVs, use the electric motor as the sole propulsion source (or “prime mover” – although more than one motor can be used as in the case of hub motors on each wheel), whereas most types of HEVs use one or more electric motors combined with an internal combustion engine (ICEs) for motive power. Figures 1 and 2 illustrate the high degree of commonality between hybrids and fuel cell vehicles. [9][10]

Figure 1: General Motors' hybrid technology

**Common components**

![Common components](image-url)
The following diagrams in Figure 3 show in greater detail the primary likely architectures for HEVs, BEVs and FCVs, as well as a few additional potential architectures for HEVs. In the “parallel” HEV system, both the electric motor and internal combustion engine (ICE) deliver power to the drive wheels. A 4-wheel drive HEV system uses two sets of electric motors; one motor powers a set of wheels like other parallel or series hybrids, and the second motor provides the sole power to the second set of wheels. BEVs and FCVs use either a battery or fuel cell to supply electricity to the electric motor, which provides all the motive power to the drive wheels. In a “hybrid” FCV, a battery supplements the fuel cell in providing electricity to the electric motor, as well as aiding in fuel cell system startup and allowing for the inclusion of regenerative braking.

There are two other potential, but at this point less popular, HEV designs – series HEVs and “plug-in” HEVs. In a series HEV, the ICE is used to power a generator that then helps to power the electric traction motor and/or charge the battery pack. The ICE used this way can run at a very narrow and efficient region of its engine map, but the series HEV system is inherently more expensive because of the need for the secondary motor/generator and the full-sized electric motor. Because they are more expensive, no automaker has yet announced plans to commercialize a series HEV. A “plug-in” HEV is an HEV that can be refueled two different ways; first with gasoline as usual, and second the battery can be recharged from an off-board source such as a garage electrical outlet as with a BEV. The rationale for this is to allow the vehicle to operate independently of the ICE with a limited “ZEV range.” In order to accomplish this, these HEVs would have electric motors capable of providing baseline vehicle power, and significant battery pack capacity in order to allow operation as essentially a battery electric vehicle. It is worth noting that both of these HEV types are somewhat more akin to FCVs and BEVs than are parallel...
HEVs because the electric traction motor is likely to be of the full-sized type (e.g. 75-120 kW for a typical light-duty vehicle).

Figure 3: Potential system architectures for HEVs, BEVs and FCVs

Parallel hybrid EV configuration

Transmission or CVT
IC Engine
Electric Motor/Gen
Power Inverter/Controls
Battery System

Series hybrid EV configuration

Transmission or CVT
IC Engine
Electric Motor/Gen
Power Inverter/Controls
Battery System

Series hybrid EV configuration (4-wheel drive)

Transmission or CVT
IC Engine
Electric Motor/Gen
Power Inverter/Controls
Battery System

Series-parallel hybrid EV configuration

Power Split Device
IC Engine
Electric Motor/Gen
Power Inverter/Controls
Battery System
Finally, note that with the Prius, Toyota has developed a vehicle that works as a series hybrid in the way that it uses extra engine power to run a generator that helps power the 33-kW electric drive motor, but this “series-parallel” hybrid also uses the ICE to provide most of the total drive system power and therefore the vehicle is more of a parallel hybrid. This integrated “Toyota Hybrid System” has blurred the distinction between parallel and series hybrids, but other models such as the Honda Civic Hybrid are of the classical parallel type.

While there was initial interest in series HEVs and there is some continuing interest in large-battery “plug-in” HEVs with ZEV range, it seems that the parallel or the series-parallel hybrid designs are most economical. These designs allow the electric motor to separately engage itself to the drive axle through the transmission, and typically have only as much battery as is needed to drive the electric motor over a specified performance regime.

In addition, HEVs also differ with regard to their degree of “hybridization.” Most analysts measure the degree of hybridization as a function of the level of reliance on supplemental power from the electric motor or battery. [11] More formally, the degree of hybridization can be calculated as the ratio of peak electric power to the sum of the peak engine power plus electric power. [12][13] Peak electric power is measured either as peak motor power or peak battery pack power. The latter may be considered to be a more accurate measurement of the maximum available electric power because the electric motor can also be powered (along with the battery) by a generator that is operated from the ICE, as in the Toyota Prius. However, the actual total on-board power may not be the simple summation of peak electrical power and peak engine power since they two may never actually peak at the same time. [12]

Analysts have adopted various general definitions to categorize different levels of hybrids. [11][12][14] Most generally, there are three types of HEVs: “mild” hybrids, “full” hybrids, and
“plug-in” hybrids. Some analysts also add a fourth category, “minimal” or “soft” hybrids, based on the use of integrated starter-generator (ISG) systems, [11][15] though other analysts do not classify these vehicles as HEVs. [16][14]

Integrated starter generator (ISG) systems that allow the engine to be shut off and turned back on at idle (i.e., “idle off” or “stop/start”), that use a 42V electrical system, and that have limited regenerative braking capability. Though some analysts call these “minimal hybrids,” this paper does not consider these ISG system-based vehicles to be true HEVs in the sense that both electrical and ICE power provides significant motive power to the vehicle. Such systems may have some regenerative braking capability, but this is limited by the small size of the generator and battery pack. They do not in the conventional sense use the motor/generator as a traction motor, though the motor may provide some additional low level of positive “launch” torque as well as helping to smooth out the power profile from the ICE by adding power in between cylinder firings. This type of system is distinguishable from true hybrid systems in that it does not require voltage levels higher than 42V, the ICE is not down sized, and the motor cannot provide sustained assist during acceleration. These 42V systems are limited to about 12 kW of power due to high resistance losses at higher current levels. [13]

Mild hybrids have idle off capability, significant regenerative braking, and the electric motor may assist the vehicle’s launch but does not allow all-electric operation during any part of the vehicle’s operation. Peak power from the electrical system is typically less than about 23 percent, as measured by the ratio of peak motor power to total power.² [12]

Full hybrids are similar to mild hybrids but with a higher percent of power from the electric motor, and the capability for all-electric drive operation during some part of the vehicle’s operation. Peak power is about 39 percent or greater. [12]

Plug-in hybrids that have extended all-electric drive capability, and batteries that are charged from off-board electrical sources (also called “range extender” or “grid-dependent” hybrids).

Toyota has an ISG system (called Toyota Hybrid System-Mild [THS-M]) on sale in Japan in its Crown sedan. It has a 3 kW motor, a 42-volt electric system, lead acid batteries, and a modest 2 percent peak power. Starting in 2004, GM plans to start selling ISG systems, called Integrated Alternator Starter Damper (ISAD), in full size pickups, and also place them in its full size SUVs in 2007. GM also plans another ISG system, called Belt Alternator System (BAS), in its Malibu midsize sedan (2007) and Chevy Equinox SUV (2006). [17]

A good example of a mild HEV system is Honda’s Integrated Motor Assist (“IMA”) drivetrain that is used in its Insight and Civic Hybrid models. This IMA system is based on a voltage level of 144V, and the Insight has a 10 kW motor and a corresponding motor peak power of about 17 percent of total system power. [12] Honda has been rumored to be considering putting the IMA system into either the Odyssey minivan, Pilot SUV, or Acura MDX SUV (all of these vehicles are built on the same platform). The Dodge Ram Contractor Special, the only diesel hybrid planned for commercialization, also appears to be a “mild hybrid.”

Meanwhile, the model year 2003 Toyota Prius (the Toyota Hybrid System [THS]) is a full hybrid that operates at a higher voltage (288 V) and that has a motor peak power of 39 percent of total system power. [12] The Prius’ 33 kW motor allows low speed, low acceleration all-electric

² Note that the California Zero-Emission Vehicle regulations use peak power of the electrical storage device (e.g., battery), rather than motor, to measure the peak power ratio.
operation, such that the vehicle can launch based on motor power alone. Ford and GM also plan to market “full” hybrid systems in compact SUVs.

The second generation Prius drivetrain that will be introduced as a model year 2004 vehicle will have an even greater level of hybridization. The new system, dubbed the “Toyota Hybrid Synergy Drive,” has a 50 kW motor operating at 500 volts. [18] It has also announced an even more powerful hybrid that it will place its luxury SUV, the Lexus RX330. The high voltage and high peak power from the electric motor, about 46 percent for the MY2004 Prius, distinguish these systems from among the full hybrid systems described above.

Finally, in Europe Renault offers a “plug-in” hybrid or “range-extender” version of a station wagon EV known as the “Kangoo.” In general, the level of commonality with FCVs increases as we move down this list, but it is important to remember than many different HEV designs are possible even within each of these categories, and in many ways HEV designs can be arrayed across a continuum rather than as a set of discrete design choices.

Table 1 summarizes the hybrids commercialized or announced for the U.S. market. Also included are recent hybrid fuel cell prototypes. This table helps illustrate the close linkage between HEVs and FCVs and how higher degrees of hybridization increase the technological linkage. In particular, the full hybrids have motors approaching or matching in size the motors for the fuel cell vehicles. The mild and full hybrids, and hybrid fuel cells all use advanced nickel metal hydride batteries. Finally, the mild, full hybrids, and hybrid fuel cells all have high power electrical system greater than 42 volts, with the newer Toyota systems having power approaching or matching the 600 volts of the hybrid fuel cells.
Table 1. Commercial and announced hybrid plans for the U.S. market, summary of key attributes

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>System Voltage</th>
<th>Motor Traction Power</th>
<th>Battery Type</th>
<th>Peak Power</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>GMC Sierra and Chevy Silverado, Integrated Starter Alternator Damper (ISAD) system, CY2004</td>
<td>42 volts</td>
<td>na</td>
<td>Pb-Acid</td>
<td>na</td>
<td>Integrated Starter Generator</td>
</tr>
<tr>
<td>GMC Yukon and Chevy Tahoe, Integrated Starter Alternator Damper (ISAD) system, CY2007</td>
<td>42 volts</td>
<td>na</td>
<td>Pb-Acid</td>
<td>na</td>
<td>Integrated Starter Generator</td>
</tr>
<tr>
<td>Chevy Equinox (2006) and Malibu (2007), Belt Alternator System (BAS)</td>
<td>36 volts</td>
<td>na</td>
<td>Pb-Acid</td>
<td>na</td>
<td>Integrated Starter Generator</td>
</tr>
<tr>
<td>Dodge Ram Contractor Special, CY2004</td>
<td>42 volts</td>
<td>na</td>
<td>Pb-Acid</td>
<td>na</td>
<td>Mild Hybrid</td>
</tr>
<tr>
<td>Honda Civic, Integrated Motor Assist (IMA), MY03</td>
<td>144 volts</td>
<td>10 kW</td>
<td>Ni-MH</td>
<td>14%</td>
<td>Mild Hybrid</td>
</tr>
<tr>
<td>Honda Insight, Integrated Motor Assist (IMA), will be discontinued after MY2003</td>
<td>144 volts</td>
<td>10 kW</td>
<td>Ni-MH</td>
<td>17%</td>
<td>Mild Hybrid</td>
</tr>
<tr>
<td>GM Saturn VUE Hybrid, CY2005</td>
<td>300 volts</td>
<td>40 kW</td>
<td>Ni-MH</td>
<td>30%</td>
<td>Full Hybrid</td>
</tr>
<tr>
<td>Ford Escape Hybrid, MY2004</td>
<td>300 volts</td>
<td>65 kW</td>
<td>Ni-MH</td>
<td>na</td>
<td>Full Hybrid</td>
</tr>
<tr>
<td>Toyota Prius, Toyota Hybrid System (THS), MY2003</td>
<td>300 volts</td>
<td>33 kW</td>
<td>Ni-MH</td>
<td>39% (29% battery)</td>
<td>Full Hybrid</td>
</tr>
<tr>
<td>Toyota Prius, Toyota Hybrid Synergy Drive, MY2004</td>
<td>500 volts</td>
<td>50 kW</td>
<td>Ni-MH</td>
<td>46%</td>
<td>Full+ Hybrid</td>
</tr>
<tr>
<td>Lexus RX330 Hybrid, CY2004</td>
<td>600 volts</td>
<td>175 kW</td>
<td>Ni-MH</td>
<td>60%</td>
<td>Full+ Hybrid</td>
</tr>
</tbody>
</table>

Examples of Recent Hybrid Fuel Cell Prototypes

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>System Voltage</th>
<th>Motor Traction Power</th>
<th>Battery Type</th>
<th>Peak Power</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ford Think Focus FCV Hybrid</td>
<td>na</td>
<td>65 kW</td>
<td>Ni-MH</td>
<td>100%</td>
<td>Hybrid Fuel Cell Vehicle</td>
</tr>
<tr>
<td>Honda FCX-V3 FCV</td>
<td>na</td>
<td>60 kW</td>
<td>Ni-MH</td>
<td>100%</td>
<td>Hybrid Fuel Cell Vehicle</td>
</tr>
<tr>
<td>Toyota FCHV (Fuel Cell Hybrid Vehicle)</td>
<td>600 volts</td>
<td>80 kW</td>
<td>Ni-MH</td>
<td>100%</td>
<td>Hybrid Fuel Cell Vehicle</td>
</tr>
</tbody>
</table>

Notes:
1. Peak power is peak rated motor power divided by total power. Total power is the sum of peak motor and peak engine power.
2. Peak power estimates calculated by authors based on published data when available.
3. For 2003 Toyota Prius, peak power is also given as peak of battery power (peak battery power divided by total power).
4. Media reports indicate Toyota will be producing a hybrid Highlander and considering a hybrid Camry, but no formal announcements have been made yet. Honda is also rumored to be considering a hybrid version of its Odyssey/MDX/Pilot platform.
4. Common components for HEVs and FCVs

As shown in the figures of the various hybrid vehicle configurations, HEVs share key components and systems with FCVs and BEVs. The common components are:

- High efficiency and torque-density electric motors and electric motor control systems (typically 8-bit or above);
- Power inverters and overall HEV power/propulsion system controllers, including software (at least 32-bit); and
- Wiring harnesses for high power circuits (if HEVs operate at greater than 60V).

The commonality is even greater if the FCV is hybridized, and this is very likely to be the case because of the need for batteries to aid in fuel cell system startup, and because it allows the fuel cell system size and cost to be reduced. In addition to the above component systems, HEVs and hybrid FCVs share:

- Batteries and battery control modules; and
- Regenerative braking systems.

Current hybrid FCV prototypes include the Ford Focus FCV, the Toyota FCHV-4, the Honda FCX-V3, the Nissan Xterra FCV, and the Daihatsu MOVE FCV-K-II. ³ [19]

The particular characteristics of the common components vary between HEVs and FCVs, depending on the exact power and energy demands required for the particular vehicle design. Most significantly, since the electric motor must supply all motive power in FCVs, the power systems and motors are more powerful than for most HEVs. Despite the fact that the exact parts may differ, a key insight is that due to the potential for “repeat” parts in different battery cell sizes of the same “footprint” so that the same battery cell lid parts assembly can be identical for a range of different cell Amp-hour capacities. This important concept -- of “design for manufacturing and assembly” -- by including as many repeat components as possible in a product line that spans several similar products of different discrete sizes -- also applies to electric motor/generators, and motor controller/inverter systems.

The “spillover” effect from HEVs to FCVs is actually already becoming quite pronounced in existing FCV prototypes that in some cases borrow identical parts from HEVs. For example, the Toyota FCHV-4 uses a drivetrain that is directly adapted from the hybrid-electric drive system

³ The engineering rationale for hybridizing FCVs is different than for ICE hybrids. On the latter, the purpose of the electric motor is to allow the ICE power to be reduced, thereby having a smaller engine that operates near to its peak efficiency region (typically around 60-70% of peak torque for most ICES) as much as possible. The battery in the HEV will typically provide all of the power needed for the motor, but some HEV designs (e.g. the Toyota Prius) also provide some of the motor power from a secondary motor/generator operating in generator mode and running off of excess engine power. For FCVs, the story is rather different from an engineering perspective. As with HEVs one main purpose of the battery in an FCV is to allow a key component to be down-sized -- in this case it is the fuel cell system rather than the ICE -- but the resulting smaller fuel cell system actually will tend to operate at lower efficiency because typical PEM fuel cell efficiency as a function of peak system power peaks at much lower relative power than for the ICE (typically at around 15-20% of peak power). The rationale for hybridizing a battery with the fuel cell in the FCV is therefore not to improve the fuel cell system efficiency, but to reduce the size and cost of the fuel cell system, as well as for other considerations. [20][21]
used in the Prius. [22] Also, there is significant overlap between the Ford Escape HEV and the new Focus hybrid FCV. The new Focus FCV has been hybridized with the addition of a 300-Volt Sanyo battery pack and a brake-by-wire, electro-hydraulic regenerative braking system. Both of these advanced technologies also are found on the company’s HEV Escape, which is due out in 2003. [23] With manufacturers striving to reduce cost in advanced vehicle development and production, there is every reason to believe that this trend will continue, and likely grow stronger, in the future.

4.1 Electric motors for HEVs and FCVs

Both FCVs and HEVs share the use of an electric motor and system power inverter/controller, although this system will vary in size for the HEVs and will typically be smaller than the motor/controller in FCVs. This is because FCVs like BEVs use the electric motor as the sole propulsion source (or “prime mover” – although more than one motor can be used as in the case of hub motors on each wheel), whereas HEVs use both electric motor and ICE prime movers. For light-duty HEVs, the electric motor(s) will typically range in size from about 10 kW to 50 kW depending on the level of vehicle hybridization and the size of the vehicle, while for light-duty FCVs the electric motor(s) will typically be in the 75 kW to 120 kW range.

At present, there are two primary choices of motor technology for use in EV drivetrains -- alternating current (AC) induction and brushless permanent magnet (BPM) – with switched reluctance motors being a third but much less used option. Both of these options offer significant advantages over conventional direct-current (DC) brush motors. These include lighter motor weights, higher efficiencies, and lower service requirements (the brushes in DC brush motors wear out and require replacement). In general, AC induction motors provide high efficiencies over a wide range of operation, while BPM motors provide higher peak efficiencies. BPM motors also tend to be lighter, but they use rare earth magnets that are somewhat costly at present. Both of these motor types require complicated control systems relative to DC brush motors, in order to operate from a DC source. Many BEV and FCV designs use AC induction motors (such as the Ford vehicles that are based on the Ecostar driveline), while others use BPM motors. Most HEVs developed in recent years incorporate BPM motors due to their higher peak efficiencies and high power/torque densities. (See Figure 4) [24]
Finally, with regard to HEV and FCV motors, it is worth noting that FCVs would also require a main compressor motor and possibly additional auxiliary motors as well as the main traction motor. Similar motor technologies, including brushless permanent magnet (BPM) motors, are being considered as fuel cell system compressor motors for FCVs as well as traction motors, and UQM Technologies Inc. is considering developing a small BPM motor for fuel cell system compressors. [25] This 10-15 kW motor, or one very similar, might also be suitable as a small traction motor for mildly hybridized HEVs.

4.2 Electric motors controller/inverters for HEVs and FCVs

In addition to the electric motors themselves, EV motors also require a power inversion and control system. Simple DC motors do not require power inversion, but both AC induction and BPM motors do require the DC power from the battery and/or fuel cell to be inverted into an AC waveform. This is accomplished through the use of insulated-gate bipolar transistors (IGBTs) as the high-power switching devices (in the past, MOSFETs were often used for this purpose). Again, the size of the motor controller/inverter will vary for various HEVs and FCVs, but controller/inverters to support different motor sizes will vary primarily in the number and rating of the IGBTs used, with the low-power side of the controller/inverter (i.e. the “controller” part) being virtually identical.

With great progress made in the performance and cost of IGBTs in recent years, these devices have become critical components of high-power EV drivelines. IGBTs are essentially a cross between bipolar transistor and MOSFET technology, thereby obtaining the high current handling ability of the bipolar transistor with the ease of control of the MOSFET. IGBTs are preferred over MOSFETs for high voltage and power applications of over about 100V and 10kW (and are the absolute choice above about 500V), while MOSFETs tend to be used for lower power applications of under about 10kW. [26]

Thus, most EVs today incorporate IGBTs in the system power inverter, and the progress made in IGBT technology, partly due to their use in BEVs and HEVs, is helping to lower the cost of FCV inverter systems. We note here that ISG systems that operate at 42V can easily use MOSFETs...
rather than IGBTs, and therefore do not contribute in the same way to reducing the potential future costs of FCV electrical componentry. All of the planned 42V ISG systems that we are familiar with use MOSFETs rather than IGBTs in the power electronics section of the system controller/inverter.

4.3 Wiring harness and power safety systems for HEVs and FCVs

HEV designs that employ power systems with DC voltages in excess of 60V (25V AC), but not exceeding 600V, are required to comply with stricter SAE standards than vehicles with systems of lower voltage, such as the 42V ISG systems. For example, systems of greater than 60V require the J1654 “High Voltage Primary Cable” standard instead of the lower-voltage standard SAE J1128 “Low Tension Primary Cable,” as well as adherence to the additional J1673 “High Voltage Automotive Wiring Assembly Design.” [27][28][29] These standards include such features as cable spark testing, insulation resistance, abrasion resistance, and pinch resistance, proper grounding for high-voltage systems (which cannot be to the vehicle chassis as in <60V systems and must instead be to battery negative terminal due to the potential for shock), and the need for active ground-fault detection. This is important because experience with high-voltage HEVs in dealing with this set of standards, that is not needed for standard ICEs and 42V ISG system vehicles, will help to smooth the path for FCVs to also comply with SAE J1654, J1673, and other relevant standards for 60V to 600V systems. (See Figure 5) Finally, experience with maintaining and repairing HEV electrical systems, including high-voltage battery, motor, and wiring systems, regenerative braking systems, electrical auxiliaries, and so on, will also produce mechanics who are more well able to perform similar maintenance and repair functions for FCVs.

Figure 5: Conventional ICE and HEV system voltage levels and SAE safety standard break points

![Figure 5: Conventional ICE and HEV system voltage levels and SAE safety standard break points](chart.png)
The following quote regarding the battery pack safety systems of the Toyota Prius gives some indication of what is necessary for these higher voltage systems: [30]

Both power cables are isolated from the metal chassis, so there is no possibility of shock by touching the metal chassis. A ground fault monitor continuously monitors for high voltage leakage to the metal chassis while the vehicle is running. If a malfunction is detected, the vehicle computer will illuminate the master warning light in the instrument cluster and the hybrid warning light in the LCD display. The HEV battery pack relays will automatically open to stop electricity flow in a collision sufficient to activate the front SRS airbags.

These safety systems are important so that vehicle occupants cannot accidentally get shocked by touching the vehicle chassis in the event of a short in the electrical system, and so that early warning of potential problems can be obtained.

4.4 Battery systems for HEVs and Hybrid FCVs

Both HEVs and hybrid FCVs use high-power battery packs of similar sizes (cell capacities) and designs, although ultracapacitor, flywheel, or other energy devices are possible. It is quite reasonable, however, to think that a battery pack that could provide about 20 kW of power and about 2 kWh of energy (i.e., ~40 Wh/kg and ~800 W/kg) would be useful for certain HEV designs as well as certain FCV designs. As noted above, a key insight is that due to the potential for “repeat” parts in different battery cell sizes of the same “footprint” so that the same battery cell lid parts assembly can be identical for a range of different cell Amp-hour capacities.

With regard to HEV and FCV battery systems, both nickel-metal hydride (NiMH) and lithium-ion (Li-ion) batteries are being incorporated into production and prototype HEVs and FCVs, along with ultracapacitors in a few models. NiMH batteries are the dominant choice at present as their performance in HEV applications has proven to be very acceptable and their costs are somewhat lower than Li-ion batteries. NiMH batteries were initially thought to be excellent BEV batteries but perhaps not the best choice for HEVs due to their relatively low power density, but as these batteries have been optimized for HEV applications over the past several years, they have achieved great increases in power density to the point that some designs are now reported to be achieving a remarkable 1000 W/kg. [31] There is intensive ongoing work to reduce the costs of Li-ion batteries by attempting so find substitutes for the costly cobalt used in the Li-ion batteries that currently offer acceptable cycle life, but again NiMH batteries appear to be somewhat less costly at present, and are therefore an attractive option for both HEVs and FCVs.

Figure 6 shows the design of three different HEV NiMH battery modules, and how the cell size can be varied while maintaining many repeat components in the battery lid/terminal assembly. [9] Note that each module has an identical width and container footprint/lid design, while the capacity of the cells varies by a factor of three. This is important because it suggests that while the exact cell sizes used for HEV and FCV battery packs may vary somewhat, development of HEV packs clearly can enable the development of battery packs for FCVs, even given the potential for differences in battery cell sizes.
Figure 6: Various sizes of NiMH battery modules for HEVs

<table>
<thead>
<tr>
<th>Size</th>
<th>HEV Cells</th>
<th>Capacity</th>
<th>Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>13-HEV-60</td>
<td>11</td>
<td>60 Ah</td>
<td>13 V</td>
</tr>
<tr>
<td>7-HEV-28</td>
<td>6</td>
<td>28 Ah</td>
<td>7 V</td>
</tr>
<tr>
<td>12-HEV-20</td>
<td>10</td>
<td>20 Ah</td>
<td>12 V</td>
</tr>
</tbody>
</table>

L = 418 mm  
W = 102 mm  
H = 119 mm

L = 240 mm  
W = 102 mm  
H = 81 mm

L = 340 mm  
W = 102 mm  
H = 91 mm

4.5 Regenerative braking systems for HEVs and hybrid FCVs

Third, hybridized FCV and HEVs are likely to both have regenerative braking systems. Depending on the driving cycle, hybrid FCV efficiencies can be higher than comparable non-hybrid versions due to the addition of regenerative braking. [32][33] An additional important consideration is the issue of fuel cell system startup time, where a battery power system is currently essential for startup and to keep the fuel cell stack from freezing in cold weather. Finally, an additional advantage of the battery pack for both HEVs and FCVs is the ability to recapture braking energy through “regenerative braking,” and these new braking systems will likely prove to be similar for these two vehicle types.

With the exception of non-hybrid FCVs, HEVs and FCVs will tend to incorporate similar regenerative braking systems in the vehicle design. These systems by themselves (i.e. excluding the battery storage system) are not expensive or complicated, and they offer the advantage of allowing the recapture of vehicle braking energy that would otherwise be lost. There are some interesting subtleties with regard to the operation of these systems and how they are actuated, and experience gained with these systems in HEVs and battery EVs will help to make them mature as they are incorporated into hybrid FCVs.

Note also with regard to braking systems in HEVs and FCVs that “brake-by-wire” systems are likely to be included in both of these vehicle types in the future. Already, the all-wheel-drive hybrid Toyota Estima minivan uses an Electronically Controlled Brake (ECB) system. This system allows for efficient wheel-by-wheel brake control, and optimum management of the vehicle’s regenerative brake system. [34] This system could be included on future FCVs that use all-wheel drive and that have four-wheel regenerative braking systems. Also, the Ford Focus FCV and Escape HEV utilize the same brake-by-wire system, which allows the system to
optimize braking between regeneration and friction for “maximum fuel economy and braking performance.” [23]

4.6 42V Integrated Starter-Generator (ISG) systems for HEVs and FCVs

Hybrids and ISG systems based on 42V power circuits fall below the SAE J1654, J1673, and other SAE standard “break-point” of 60V DC, and therefore require wiring and grounding standards typical of conventional vehicles with 14V auxiliary systems. HEVs with significant motor power where the electric motor is truly used as a traction motor typically are operated at voltages of at least 100V (even the 10-kW motor in the Honda Civic Hybrid runs on a nominal 144V battery system, and the Prius battery pack nominal voltage is 288V). Since 42V ISG systems are relatively novel, several design possibilities are possible and it is unclear at this time exactly what type of motor/generator will become dominant for use in this ISG application. Thus, it is difficult to assess the extent to which these 42V motors and controller/inverters might overlap and provide synergies with the larger and higher voltage systems used in full HEVs, BEVs, and FCVs, but as noted above their power electronics are likely to be MOSFET rather than IGBT based, and we expect the linkages between these systems and the higher voltage systems used in FCVs to be minimal. However, as noted below, some of the 42V auxiliary systems that are developed for use in these 42V ISG-based vehicles may also be used in future FCVs, with the aid of a DC-to-DC converter to provide the 42V voltage level.

4.7 Vehicle chassis and auxiliaries for HEVs and FCVs

In addition, HEVs and FCVs may have the potential for platform synergies and common use of some additional components such as auxiliary systems that are based on the emerging 42V standard, and various sensors and gauges used in the electric driveline. With regard to innovative platform designs, with the Chevy Triax General Motors has developed a new vehicle platform that utilizes a common lightweight body-on-frame concept along with a modular chassis design. The vehicle can be configured as an ICE vehicle, an HEV, or a BEV, and the vehicle can accommodate up to three propulsion units. The front third of the vehicle holds an electric motor in the electric and hybrid versions, the rear third of the vehicle holds the ICE in the engine-only and hybrid versions and an electric motor in the electric and hybrid versions, and the middle third houses the vehicle's energy storage – gasoline for the engine and batteries for the electric motors. [35] With this flexible design, one could certainly imagine incorporating a fuel cell system into the two rear compartments in place of the ICE and gasoline fuel tank, while making use of the same front and rear drive motors, power electronics, and regenerative and other auxiliary systems.

Furthermore, HEVs and FCVs are likely to share similar innovations with regard to overall vehicle design, including such aspects as vehicle “road load” reduction (through vehicle drag, rolling resistance, and mass reduction) and high-efficiency auxiliary systems. The details of these design changes/optimizations will vary from manufacturer to manufacturer and from vehicle model to model, but previous research has shown that there are potential advantages to spending some capital on development and manufacturing costs associated with these measures, because they can enable even greater cost reductions by downsizing vehicle drive system and related components. [36][37]

4.8 Hydrogen fueling systems for hydrogen HEVs and FCVs

Finally, while few prototypes have been built to date, HEVs could be made to operate on hydrogen as a fuel rather than gasoline (or could operate on CNG or other fuel). Hydrogen is
relatively difficult to store onboard vehicles, and is not at present a leading contender to be considered for combustion engines because of the even greater difficulty of storage than with FCVs (which would be more efficient and need to store comparably less to achieve similar driving range). However, when coupled with a more efficient hybrid driveline, then the use of hydrogen ICEs in HEV drivelines becomes potentially more attractive. Development and use of hydrogen HEVs would help to enable the development of the critical hydrogen infrastructure needed for ZEV “gold standard” FCVs, as well as lending operational experience and maintenance and support services development for hydrogen as a vehicle fuel.

5. Manufacturing Learning Curves

Global HEV production efforts will allow production volumes of key components to increase in advance of FCV commercialization, thus helping to “pave the way” for FCVs once larger-scale production efforts are initiated to bring them to market. Economy-of-scale based cost reductions coupled with product innovation and manufacturing process innovation drive down costs as the manufacturing history of a product proceeds. This can be plotted in terms of the cumulative production versus the cost of the product, and these curves are known as “learning curves” or “manufacturing experience curves.” One example of a classic manufacturing experience curve is for the Model-T Ford, shown below as both normal and log-log plots. These plots illustrate the general logarithmic nature of the effect that has often been observed, but many such curves have been plotted.

The “central tendency” for the learning/experience curves that have been examined for various commercial products to date is for cost reductions of approximately 20% with each doubling of accumulated production of a product, with a typical range of 10% to 30% (see Lipman and Sperling, 2000, for a literature review and application of manufacturing experience curves to forecasting the costs of PEM fuel cell systems). [38] The Model-T curves below in Figures 7 and 8 show an 85% manufacturing progress function or “experience curve” fit to the data, which translates into a 15% reduction in manufacturing cost with each doubling of cumulative production. [39]

Figure 7: Price path of Model-T Ford (1909-1923) with standard scale
Excellent examples of this include the progress that we have already seen in battery EV and HEV design improvement and cost reduction, several examples of which are cited below. These include innovations in electric drive systems, where electric motors have improved in power and torque density and motor controllers have decreased in size and cooling load, and innovations in batteries that have translated into improved power density and other characteristics. It is this powerful combination of product improvement, manufacturing process improvement, and economies of scale in production that can produce large reductions in cost such as in the examples below.

As in other products that have improved over time and experienced reductions in cost, with BEVs and HEVs we again are seeing a great deal innovations and progress in the design of key vehicle components. Statements made by automakers in the late 1990s, after several years of research and prototype vehicle production, give evidence of this progress. This can have direct benefits by driving down costs of key subcomponents that are common to systems in both vehicle types, and it can also have secondary effects such as providing component suppliers with revenue and resources to pursue R&D in other related systems for other electric-drive vehicle types. Many electric-drive components offer the potential for strong economies of scale, and learning/experience in product and process design is also helping to lower costs (see Lipman, 1999a and 1999b, for examination of the potential for cost reductions through higher volume production and improvements in electric-drive systems and EV/HEV NiMH batteries). [40][41]

In addition to production scale economies, product innovation will lead to reduced electric drive system costs as the EV market matures and further manufacturing experience has been gained. These improvements will surely begin to reach a limit at some point, but there is no indication that these limits have been reached yet, particularly for motor inverter power electronics (IGBTs), motor controls, and overall HEV/FCV system control units.

5.1 Electric motors

Figure 9 shows the reduction in manufacturing costs of new vehicle technologies that is expected to come with economies of scale in production a 50-kW BPM motor. Although HEV motors are typically smaller than FCV or BEV motors, advanced motors can also capture economies of scale across product sizes by using many repeat components. Leading HEV motor supplier Unique
Mobility Inc. reports that among their 30 kW, 50 kW, and 80 kW traction motors for electric-drive vehicles, there are many repeat components and that a large order for the 30-kW motors would help to “drive down” the costs of the larger motors at the same time. [25]

Figure 9: OEM cost versus production volume for 50-kW BPM motor

5.2 Electric motors controller/inverters

As discussed above, the size of the motor controller/inverter will vary for various HEVs and FCVs, but controller/inverters to support different motor sizes will vary primarily in the number and rating of the IGBTs used, with the low-power side of the controller/inverter (i.e. the “controller” part) being virtually identical. Again, many repeat components can be used, and the IGBT devices themselves are modular with strong production economies of scale.

In recent years the costs of IGBTs and electric vehicle motor controller/inverters in general have declined considerably through design and manufacturing innovations, and we have already seen the impact of the early EV/HEV market in helping to drive down costs of power electronics for future advanced electric-drive vehicles. John Wallace of Ford has reported significant progress in the development of Ford/Ecostar’s electric drive system: [42]

[W]e have gone down in numbers and parts in the controller – it started out quite complicated. I can remember the original Ecostar controller, which was quite complex; then there was a two-board controller and now a one-board controller, and perhaps we will go down to a no-board controller basically by mounting control circuitry right on the motor. All that stuff is tearing out cost.

Also, Robert Purcell of GM reported back in 1998 that the second generation EV-1 motor controller included only three insulated-gate bipolar transistors (IGBTs) in the inverter section, while the first generation had six. The newer IGBTs used in the second generation controller have twice the power handling capability of the older ones, with equal precision levels and lower total
Overall, the second-generation, electric-drive control system had half the mass, one-third fewer parts, and half the cost of the first generation system. [43]

5.3 Batteries

As discussed previously, there is great potential for “repeat” parts in different battery cell sizes of the same “footprint” so that the same battery cell lid parts assembly can be identical for a range of different cell Amp-hour capacities. In addition, batteries of different capacities, though different in design, use the same basic materials such as, in the case of NiMH batteries, metal hydride materials, nickel hydroxide, nickel “foam” substrate materials, and so on. Commercialization of these batteries today is helping to drive down the costs of producing these materials (which are “value-added” products themselves and not simply raw materials), and this is helping to drive down the costs of all batteries that use those same materials.

Toyota and Panasonic have experienced great progress in improving the performance of the NiMH batteries used in the various generations of the Prius, starting with cylindrical or “spiral wound” cells in the first generation and then continuing on with higher power density “prismatic” battery cells in subsequent generations. In this progression, Panasonic increased the power density of the Prius battery by more than 75% from the first to the second generation of the battery pack, from 500 W/kg in the first version to 880 W/kg in the second. [44]

6. Conclusions

In conclusion, HEVs clearly offer many opportunities to help provide innovative systems, key component cost reductions, and maintenance “infrastructure” and experience that can help to improve the chances for successful commercialization of FCVs. HEVs can reduce costs of common components with FCVs through the combination of basic economies of scale, the accumulation of manufacturing experience, and product design innovations. In the case of HEVs and FCVs, key common components include electric motor and motor controller/inverter systems, battery or ultracapacitor systems, regenerative braking systems, high-voltage safety systems, overall vehicle system controllers, and other auxiliary systems such as brake and drive-by-wire.

Key insights that are noted above include that even though the basic reasons for hybridizing HEVs and FCVs are fundamentally different in certain respects, many common components are likely to be present in various HEV and FCV designs, and that even though the exact details of the sizing of certain components will vary, the many common or repeat parts that they employ still offers many opportunities for cost reductions.

With regard to this potential, there are really four main categories of HEVs: 1) 42V ISG systems with engine stop/start and regenerative braking (that many analysts including ourselves do not consider true HEVs); 2) “mild” HEVs that in addition include the ability for the electric motor/generator to truly act as a traction motor in parallel hybrid mode, but that do not allow for all-electric operation; 3) “full” HEVs that also include the capability for electric launch and may include some “ZEV range;” and 4) true series or “range extender” HEVs that like battery EVs and FCVs have a full-sized electric motor and only use the ICE to recharge the battery pack.

These four categories of HEVs have greater and greater linkages to FCVs, respectively, but in a sense there is really a continuum of options and there are also many subtleties and blurred distinctions that complicate the picture. The 42V ISG systems have relatively little in common
with FCV systems due to their relatively low voltage and the fact that the motors and motor controllers used for these small low voltage systems are rather different than the higher-voltage systems for HEVs with larger traction motors. Regenerative braking systems may be the main connection between these vehicles and FCVs. The relatively “mild” hybrids have more in common with FCVs because they will tend to use similar motor/controller systems as will FCVs, albeit lower power ones. Next, the “full” HEVs with larger motors and full electric launch capability have electric-drive systems that are even closer to those likely to be used in FCVs, again due to the larger electric drive system and the higher system voltages that are likely to be used. Finally, the series or “range extender” HEVs are the closest in design to FCVs due to their full-sized electric motors and likely similar system voltages of greater than 300 volts. However, the new, more powerful Toyota “full” hybrid systems (MY2004 Prius and RX330 hybrid) also have motors and electric systems approaching those of fuel cell vehicles.

Key “break-points” with regard to the degree to which certain HEV designs may help to enable the introduction of “true ZEV” direct-hydrogen FCVs are thus the presence of a full-sized motor (though even smaller motors of similar types do much to drive down costs of larger motors as discussed above), system voltage levels of greater than 60V that then necessitate compliance with “high voltage” SAE safety standards, and the degree to which the electric motor/generator in the HEV system acts as a traction motor in a continuous sense when needed, rather than simply as an ISG and/or ICE “drivability smoothing” device. An additional possibility is the use of hydrogen as a fuel for HEVs, and the resulting benefit for FCVs of helping to initiate the development of a hydrogen fueling infrastructure. These break points may be useful in understanding the differences among HEV designs, and the degree to which each type of design shares common components or other traits with “true ZEV” hydrogen FCVs. Since FCVs appear at present seem to offer the greatest long-term hope for reducing the environmental impacts of motor vehicle use, the impact of HEVs in enabling the eventual commercialization of FCVs may prove to be vitally important.

Finally, the additional incentives for HEVs in California’s April 2003 ZEV amendments appear to be well justified in terms of promoting hybrid designs based on their degree of technological linkage to pure ZEVs. [45] The 2003 amendments establish credit cut-off points based on electrical power (less than or greater than 42 volts) and motor size (10 kW and 50 kW levels). These modified ZEV regulations provide increased incentives for HEV production, and based on the linkages discussed in this paper, are likely to advance the cause of pure ZEV, especially FCV, commercialization as well.

7. Acknowledgments

The authors would like to acknowledge the assistance of David Friedman, Feng An, Brian Johnston, and Anthony Eggert, for their technical comments during the preparation of this paper. Of course, the authors alone are responsible for the paper’s contents and findings.

8. References


[45] California Air Resources Board (CARB), 2003, Resolution 03-4, Agenda Item No.:03-02-4, April 24.
9. Authors

Dr. Timothy E. Lipman is Executive Director of the Center for Interdisciplinary Distributed Energy Research (CIDER) at UC Berkeley. Dr. Lipman's studies focus on fuel cells, electric and hybrid vehicles, combined heat and power (CHP) systems, renewable energy, hydrogen infrastructure, and other clean energy technologies from an integrated economic, engineering, public policy, and environmental perspective. Before joining UC Berkeley, Dr. Lipman completed a Ph.D. in Environmental Policy Analysis with the Graduate Group in Ecology at UC Davis in December 1999, and then served as Associate Director of the Fuel Cell Vehicle Center at ITS-Davis through August 2000.

Roland Hwang is a senior policy analyst with the Natural Resources Defense Council. Mr. Hwang has experience in energy demand forecasting and air pollution regulation. Before joining NRDC, Mr. Hwang was the Director of the Transportation Program for the Union of Concerned Scientists (UCS). He has also worked for the U.S. DOE at Lawrence Berkeley National Laboratory (LBNL) and the California Air Resources Board (CARB). Mr. Hwang received a BA in 1986 and an MS in 1988 in Mechanical Engineering from the University of California at Davis. He also received a Masters degree in Public Policy from the University of California at Berkeley in 1992.