Perspectives on Fuel Cell and Battery Electric Vehicles

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Presented at the CARB ZEV Workshop
December 5, 2002

I have been closely following the ZEV mandate since it was adopted in 1990. In the early years of the mandate, EVs were the ‘new thing’ and were the darlings of the media. Over the years the mandate has been changed, delayed, and weakened under tremendous pressure from automakers. When I started to read the background information describing the latest round of proposed changes, I was initially encouraged to see on the first page that the pure ZEV was still going to be a requirement. However, after reading the document through, I had the sinking feeling that the proposed new regulations spelled the death knell for zero emission vehicles.

I say this because it appears that CARB has effectively given up on battery electric vehicles, and is placing a high risk bet that fuel cell vehicles will in fact become practical in the future. While this may in fact happen, it is not at all certain. There was a lot of publicity earlier this week about fuel cell vehicles from Toyota and Honda entering service. Toyota’s press release headline from Monday this week proudly proclaimed their fuel cell vehicle to be “Market Ready”. This is of course a tiny exaggeration. As John O’Dell reported in Tuesday’s LA Times: “Representatives from both companies call the deliveries historic, but they cautioned that it will be decades before motorists can walk into a dealer’s showroom an drive away in one of the vehicles.”

But are fuel cell vehicles really the holy grail – the end game for providing clean personal mobility? The popular and accepted view is that they are. The thinking goes along the lines of: fuel cells far more efficient than an IC engines because they are based on an electrochemical process rather than combustion; they are quiet, there are no moving parts, no greenhouse gas emissions, only pure water for emissions, and will have far more range than battery electric vehicles. It sounds great.

But today I want to share with you some perspectives on fuel cell and battery electric vehicles that differ from the conventional wisdom.

First – what about driving range and efficiency of fuel cell vehicles – where is the data? There have been a lot of pronouncements but not much in the way of data. Actual range and hydrogen consumption data are very closely held, but there are some indications that might indicate that there are problems with range and efficiency.

In the Michelin Bibendum challenge last year, the fuel cell vehicles that participated drove relay-style in legs of only 30 miles between Fontana and Las Vegas. The vehicles were tested for efficiency as part of the event – but the companies that brought the fuel cell vehicles made it a condition of their participation that the actual hydrogen consumption data not be released.

Another example is the ride and drive event at the Future Car Congress in Washington DC this past summer. A number of fuel cell vehicles along with hybrids, a battery electric, and a diesel were made available for test drives over a very short course – about a half mile. During the course of the day, only the fuel cell vehicles had to leave the ride and drive to go refuel. Not even the battery electric RAV4 had to do this.

There was recently rally for fuel cell vehicles driving down Highway 1 between Monterey and Santa Barbara, a distance of 250 miles. There were <u>four</u> refueling stops set up along the way. Finally, the California Fuel Cell Partnership 2001 highlights showed 754 hydrogen refueling events for the 34,000 miles covered by the fuel cell vehicle fleet, or about 45 miles on average between refuelings.

When automakers quote range in their press information, we don't know what the test cycle is. But it seems to be of the 'up to so many miles' kind of figure. I've asked engineers that work on fuel cell vehicles what the range is, and at first I get a stock answer – something like "100 miles". Then I ask is this the urban cycle range? "well, no". "What is the urban cycle range?". "Lower". "A lot lower?" "yes".

The range problem might be overcome by a future hydrogen storage breakthrough that would allow enough hydrogen to be stored on board to match the range of what drivers are used to. But what about fuel economy? How much hydrogen do fuel cell vehicles consume per mile traveled? This is a more important metric than how efficient a fuel cell stack is at a particular operating point. The amount of Hydrogen stored or consumed is conveniently measured in kilograms. It turns out that a kilogram of hydrogen contains very close to the same amount of energy as a gallon of gasoline -- about 33 kWh. This is at best converted into about 16 kWh of electricity in a fuel cell system.

Mr. Norihiko Nakamura, Toyota Executive Advisory Engineer for fuel cell development, said at the 2002 Future Car Congress that the best fuel economy that fuel cell vehicles can achieve is about 62 miles per kg of hydrogen (or about 62 miles per gallon equivalent). In fact, Toyota claims 64 miles per kg as the uncorrected combined fuel economy from in-house testing – quite impressive. The EPA recently completed testing of the Honda FCX. For 2003, the EPA now lists two ZEVs: one battery electric vehicle – the RAV4EV, and one fuel cell vehicle – The FCX. The test results shown here for the FCX are corrected to window sticker values. The uncorrected number to compare with the Toyota FCHV is about 58 miles per kg. The window sticker for the FCX shows the expected average consumption at 50 miles per kilogram. But today's hybrid vehicles, the Honda Civic and Toyota Prius, essentially match these numbers with 57 and 58 mpg uncorrected combined EPA ratings.

2003 Honda FCX	
Miles per kilogram of hydrogen 51 city 48 hwy Annual Fuel Cost: **$1515***	
EPA Air Pollution Score	Best 10 (0–10)
Range	170 miles
Fuel	Hydrogen
Fuel Cell	Polymer Electrolyte Membrane
Motor	60 kW DC
Energy Storage Device	Ultracapacitor

*Annual fuel cost is estimated assuming 15000 miles of travel per year (55% city and 45% highway) and a fuel cost of $5.05 per kilogram of gaseous hydrogen.

2003 Toyota RAV4 EV

Electric Vehicle

Possible Tax Incentives

Use your Gas Prices   Switch to Metric units

Fuel Economy	
Fuel Type	Electricity
Energy Consumption(city) (kW-hrs/100 miles)	27
Energy Consumption(hwy) (kW-hrs/100 miles)	34
MPG (city)	125
MPG (highway)	100
MPG (combined)	112
Annual Fuel Cost	$362

30 to 60 miles per gallon equivalent doesn’t sound too bad at first, but when you consider what goes into getting the hydrogen in the first place, the picture is not so rosey.

The Toyota FCHV is based on the Highlander sport utility vehicle. With it’s fuel economy rating of 64 miles per kg, the FCHV appears to be the most efficient fuel cell vehicle, more than twice as efficient than the base Highlander with rating of 28.2 mpg. With four 5000 psi hydrogen tanks holding a total of 3 kilograms of hydrogen, you could theoretically drive 192 miles if you can match the uncorrected EPA test results. (Toyota claims a “maximum” range of 180 miles and a realistic range of 150 miles). It is interesting to estimate the performance that might be expected from hypothetical natural gas hybrid version of the Highlander. Based on the fuel economy of the Prius relative to conventional cars, it could be expected that a natural gas hybrid highlander would have an uncorrected combined fuel economy rating of about 42 mpg. Not nearly as good as the FCHV’s 64 – or is it? If the hydrogen is produced with natural gas, then expressing the FCHVs fuel economy based on natural gas consumed in making the hydrogen brings it back to the same 42 mpg. In round numbers, you need to start with 1.5 units of natural gas energy for every one unit of hydrogen energy stored in the high pressure tank on the vehicle. So there is no energy or CO2 benefit of the fuel cell version. There is a very small emissions benefit – but CNG SULEVS are already considered clean enough to qualify for solo carpool access. A benefit of the CNG hybrid version is that the driving range would be a whole lot better; even though it uses on-board fuel energy at a 42 mpg equivalent rate vs. 64 for the fuel cell version, the same tanks would hold about 3.2 times more energy in natural gas as compared to hydrogen, yielding a driving range that would be 2.1 times greater, or about 400 miles.

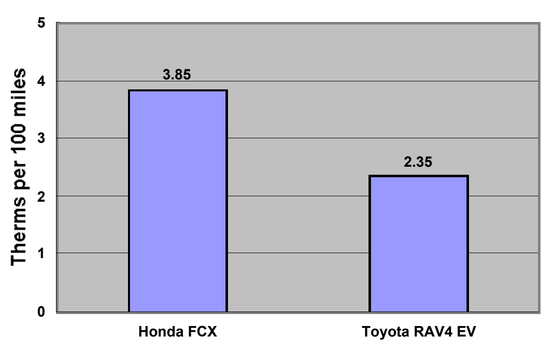
The popular long term future vision for fuel cell vehicles is that the hydrogen would be made by electrolysis with renewable electricity. The flaw in this argument is that it is not fair to claim the cleanest form of electricity generation to a particular type of load, leaving the dirtier electricity generation to everyone else. Calculations of the upstream emissions associated with recharging battery electric vehicles are usually based on the average power mix; not by singling out the cleanest electricity just for EVs. All forms of generation involve some form of impact; there is always something about any form of generation that someone won't like. So it certainly matters how much electricity is needed per mile traveled.

According to Stuart Energy Systems, it takes about 60kWh of AC electricity to make and compress one kg of hydrogen. Let's compare the electricity used to make hydrogen with the electricity to charge batteries for the two EPA certified ZEVs – the Honda FCX and the Toyota RAV4EV. With the FCX the EPA says a kilogram of hydrogen is good for 50 miles. So the AC electricity usage is 1.2 kWh/mile. By contrast, the RAV4EV has a combined city/highway energy consumption rating of only 0.3 kWh/mile –a factor of four lower. This is about the same relative difference as between a Cadillac Escalade and a Honda Insight. That electricity for the fuel cell vehicle won't be cheap as it is with EVs. With off peak rates, it would cost just under $5.00 for that 50 miles worth of hydrogen; with regular rates it could be $14 or more. Refueling time could be a problem too if done at home. With the same 32-Amp 240-Volt power used for EV charging, an electrolyzer could make only about 1 1/4 kg of hydrogen (good for 62 miles) running flat out for 10 hours – typical of off-peak charging from 9:00 p.m. to 7:00 the next morning. That's only six miles of range recovery per hour.

The figure below sums up the relative fuel consumption for 100 miles of travel for the two 2003 certified ZEVs. On the left is the case where natural gas is the base energy source. It is assumed to be converted to hydrogen with a reformer for the FCX, and is burned in a modern combined cycle powerplant to make electricity to charge the RAV4. It takes 64 percent more natural gas to go the fuel cell route. On the right is the case of using electricity as the base energy source, such as would be the case with wind energy. The difference here huge – a factor of four.

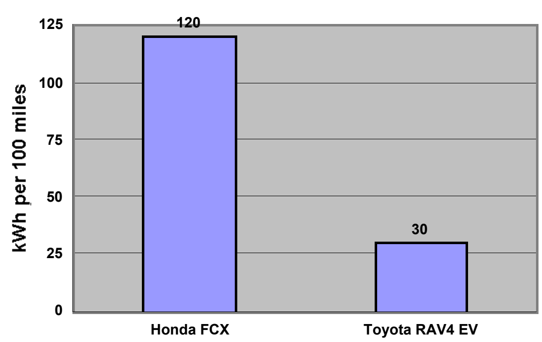
Natural Gas use per 100 miles

- Hydrogen from natural gas reformer
- Electricity from combined cycle power plant (7000 BTU/kWh)



Electricity use per 100 miles

- Hydrogen from electrolyzer



If new wind or solar generating capacity is built specifically to support zero emission vehicles – it really does matter what kind of vehicle it is used for. For a given amount of vehicle-miles per year -- Fuel cell vehicles will need to have 3 to 4 times as much land or other resources dedicated for generation as compared to battery electric vehicles

And finally there is the cost issue. If there are concerns that battery electric vehicles are too expensive to manufacture, there should be even greater concerns about fuel cell vehicles. At the Future Car Congress this past June, Toyota's Norihiko Nakamura said the following in his remarks about fuel cell vehicles:

> "If a certain level of mass production can be achieved the cost should be dropped drastically. *But a great amount of effort is needed to bring the cost to even two to three times that of a standard vehicle*"

Think about it – this is the view from Toyota, the company that knows how to manufacture and sell the Prius profitably for 20,000 dollars.

Battery Eectric Vehicles

There has been some disappointment expressed by members of the board that battery technology for electric vehicles hasn't progressed nearly as much as had been hoped. The reality is that battery technology has progressed significantly in the last decade. But vehicle manufacturers haven't been applying that technology in new products. It is interesting to look at what kinds of battery electric vehicles we could have had by now and to compare them with fuel cell vehicles. The results may surprise you.

I will comment on three types of batteries: Lead Acid, Sodium Nickel Chloride, and Lithium Ion. There are of course other types of batteries such as nickel metal hydride that work well in EVs and that bear a renewed look.

Here is a 4 passenger lead-acid powered Volkswagen Golf. It is fun to drive with about 180 horsepower and it works very well for commuting. The total cost for the battery modules in this car is only $1400. This is based on a quote from the battery manufacturer. The range is adequate – about 60 to 70 miles. (As an aside, CARB should stay away from any ZEV regulatory structure that dictates or rewards range. That could be construed as regulating efficiency. The risk I see in the proposed regulatory structure is definition of vehicle types by range capability. It might be reasonably argued that the most cost effective way to meet some range target is to improve vehicle efficiency rather than put in a larger or more expensive battery pack. That could be an opening for future attacks on the mandate from Automakers on the basis of preemption of the Federal fuel economy laws.)

180 HP, 60-70 miles range, $1400 battery pack

The sodium nickel chloride battery, also known as the Zebra battery, is an advanced technology that is now coming to market. With 120 Wh/kg, the specific energy is four times that of lead acid. The price in low volume is $500 per kwh. For high volume, the price will be $220 per kWh. Life is at least 1000 cycles and calendar life is long too. We are looking into retrofitting a GM S10 EV with two Zebra packs and an AC Propulsion drivetrain. Empty weight will be reduced several hundred pounds and the range should be 200 miles.

Zebra Battery

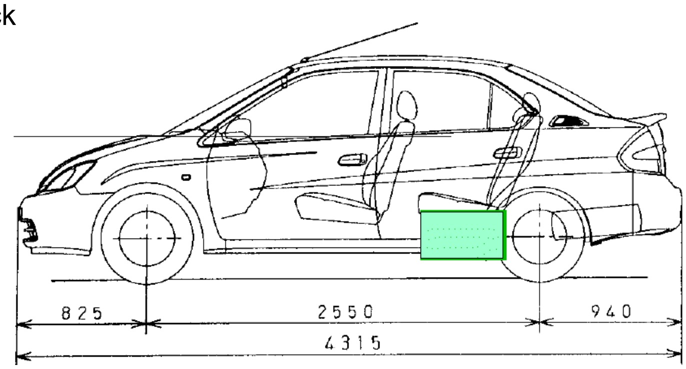
- In production in Switzerland
- 120 Wh/kg for pack (4x lead acid)
- 1000 cycles at nameplate rating
- No calendar life issues
- Pricing:
  - Low volume $500/kWh
  - High volume $220/kWh (24 kWh pack: $5280)

To demonstrate the type of EV that could be made with the ZEBRA battery, we have developed a concept based on the Prius. The Prius includes most of what you need to make a basic EV – electric drivetrain, electric power steering, electric power brakes, 4 door lightweight body, low rolling resistance tires, all for a retail price of $20,000. A 24-kWh Zebra battery pack will just fit under the rear seat. Range should be 140 miles. Using the existing Prius drive motor, it would be a low power EV suited for urban travel, but would be freeway capable. (A minor modification to the Prius transmission would eliminate the 41mph limit on electric power alone.) The battery should last at least 10 years and 100,000 miles.

Prius EV Concept

- Range 140 miles
- Weight same as standard Prius
- Cost to make same as standard Prius (+/- 10%)

- Parts added:
  - 24 kWh Zebra battery pack
  - Charger and inlet
- Parts removed:
  - Hybrid battery pack
  - Engine
  - Radiator
  - Ring gear
  - Fuel tank
  - Engine control unit
  - Exhaust aftertreatment system



The cost picture looks pretty good for this vehicle. In low volume as a conversion of the standard Prius, the main parts costs would be the Prius – $20,000, the battery pack – $12,000, and the charger -- $1500, or a total of $33,500. But there would be quite a few leftover parts which might have some residual value: These include the NiMh hybrid battery pack, the IC engine, the fuel injection system and engine control computer, the exhaust aftertreatment system, the fuel tank and evaporative emissions hardware, and the radiator. The costs look even better if this vehicle were produced in higher volume by Toyota as a ZEV in the first place. Then all costs for all those extra parts would not need to be incurred in the first place, and the battery cost would be down to $5300 (This is from the manufacturer of the Zebra battery). The manufactured cost would be very close to that of the standard hybrid Prius, possibly lower. The vehicle weight would be about the same as the standard Prius too.

Lithium Ion batteries hold much promise for vehicle application. The best lithium ion batteries pack 40 percent more energy per kilogram than the Zebra battery, and five times as much as lead acid. All of the action in lithium ion batteries has been for consumer applications – laptops, cell phones, and hand held computers. There is intense competition in this market; performance keeps going up and prices keep coming down.

We recently purchased a few kWh worth of small Lithium Ion cells. The price was $490/kWh. By contrast, our price from Panasonic for lead acid batteries has been $500 per kWh. In very high volume these lithium batteries sell for only $257/kWh. We are exploring the possibility and practicality of using these 2-Amp –hour cells in an EV. A large number of cells would be required but the costs might be acceptable.

Lithium Ion Batteries

- 18650 Cell size
- High volume production now
- 173 Wh/kg (>5x lead acid)
- 500 W/kg
- Cost
  - $412/kWh, Volume: 1 car
  - $257/kWh, high volume
  - Ref: Panasonic lead-acid, $500/kWh
- No barriers apparent to automotive application

Sample EV sized module - 100Ah

Prius pack: 4320 cells, 34 kWh, 200 kg, $7700, 160 - 200 miles range

We've looked at putting a pack of these lithium ion cells into the Prius EV described above. The energy on board would be about 34 kWh and the vehicle weight would be on about the same as the stock Prius. Range would be between 160 and 200 miles.

Below is a comparison of this vehicle to the Ford Focus FCV. They are both compact four door sedans and have essentially the same driving range. But the Prius weighs 700 pounds <u>less</u> than the Focus FCV. The Prius EV power system takes up less volume than the Focus's fuel cell power system, resulting in more interior room and a much bigger trunk. If the Focus was refueled with hydrogen produced with electricity, it would take 240 kWh to produce the 4kg of hydrogen it needs to refuel. The Lithium Prius EV would need only 38 kWh – for the same driving range.

	Focus FCV	Prius LiIon EV concept
Range	200 miles	160 - 200 miles
Energy Storage	4 kg Hydrogen	34 kWh LiIon
Curb Weight	3528 lb	2800 lb
Electrical Energy to refuel	240 kWh	40 kWh

If the Prius EV were loaded down with more lithium batteries to equal the weight of the Focus FCV, it would have 400 miles range.

Another good example is a comparison of the Honda EV plus and Honda FCX, which is based on the EV plus. The EVplus weighed in at 3590 pounds, including 950 pounds of nickel metal hydride batteries. The FCX comes in higher at 3837 pounds. The FCX EPA range is 170 miles, about twice that of the EVplus. But consider what would happen if the EVplus were fitted out with a sufficient amount 2003-technology lithium ion batteries to bring its weight up to that of the FCX. That lithium ion pack would deliver 75 percent more electrical energy than is produced by the fuel cell system in the FCX!

How about a battery electric Toyota Highlander? Even with many special lightweight body components, the FCHV weighs in at 4100 pounds, 616 pounds more than a 4 cylinder Highlander. An all electric 4100-lb Highlander employing lithium Ion batteries would have range of more than 300 miles.

Finally, here is the GM Hy-wire – the most expensive concept car GM has ever built at $10 million. This 4 door weighs in at 4180 pounds – about as much as a 7 passenger minivan. Those three hydrogen tanks in the 11-inch-thick skateboard chassis hold 2 kg of hydrogen. The range is only 60 miles. With higher pressure 10,000 psi tanks, the range would increase to only 100 miles.

Weight:	4180 lb
Hydrogen storage	2 kg @ 5000psi 3.36 kg @ 10,000 psi
Range	60 miles (5000 psi) 100 miles (10,000 psi)

Below is a 4 door EV we built at AC propulsion. It has a range of 90 miles and weighs 3110 pounds – more than 1000 pounds <u>less</u> than the Hy-wire. If it had a big lithium ion pack that brought the vehicle weight up to 3700 pounds, still 480 pounds less than Hy-wire, it would have a range of 400 miles.

	NiMh	LiIon
Weight:	3110 lb	3700 lb
Range:	90 miles	400 miles

In summary, these are the major points to keep in mind:

- Battery electric vehicles based on the same platform as fuel cell vehicles can have greater range than the fuel cell version if latest battery technology is employed.
- Making hydrogen with electricity is very inefficient. Compared with battery electric vehicles, electricity consumption will be from 3 to 6 times higher per mile.
- When hydrogen is produced from natural gas, fuel cell vehicles can, at best, only match the fuel economy of a comparable natural gas hybrid vehicle, and will have less than half the driving range for given tank volume and pressure.

With these challenges with fuel cell vehicles, why are automakers putting so much emphasis on them and hoping that battery electric vehicles will go away? I have a couple of thoughts on why this might be so. First is that decision makers in the auto companies and the government may have never been through the numbers in the way I have shown. Second, is that automakers seem more comfortable with R&D and demonstration programs, but really don't like putting advanced technology vehicles out on the market. Working on fuel cell vehicles gives automakers an excuse to ask for relief on battery electric vehicles – which can be brought to market now at very little cost penalty. But when Toyota – the company that sells the Prius for $20,000 and makes a profit – says that only after a great deal of effort will fuel cell vehicles come down to 2 to 3 times the cost of conventional vehicles, you can see the writing on the wall that we'll be back here again in ten years hearing all about why fuel cell vehicles can't be produced for general use.

With the new proposed regulations, I fear that CARB is now poised to snatch defeat from the jaws of victory. Really good battery electric ZEVs are now possible; now is not the time to give up on them. Do not bet the farm that fuel cell vehicles are just around the corner. The ZEV mandate should not single out fuel cell vehicles for extra large credits and should not provide credit for fuel cell infrastructure. Fuel cell and battery ZEVs should be on equal footing. Let fuel cell vehicles sink or swim based on their merits, and please don't structure the revised mandate in a way that would in essence abandon the only kind of true ZEVs that have already made it to end users.